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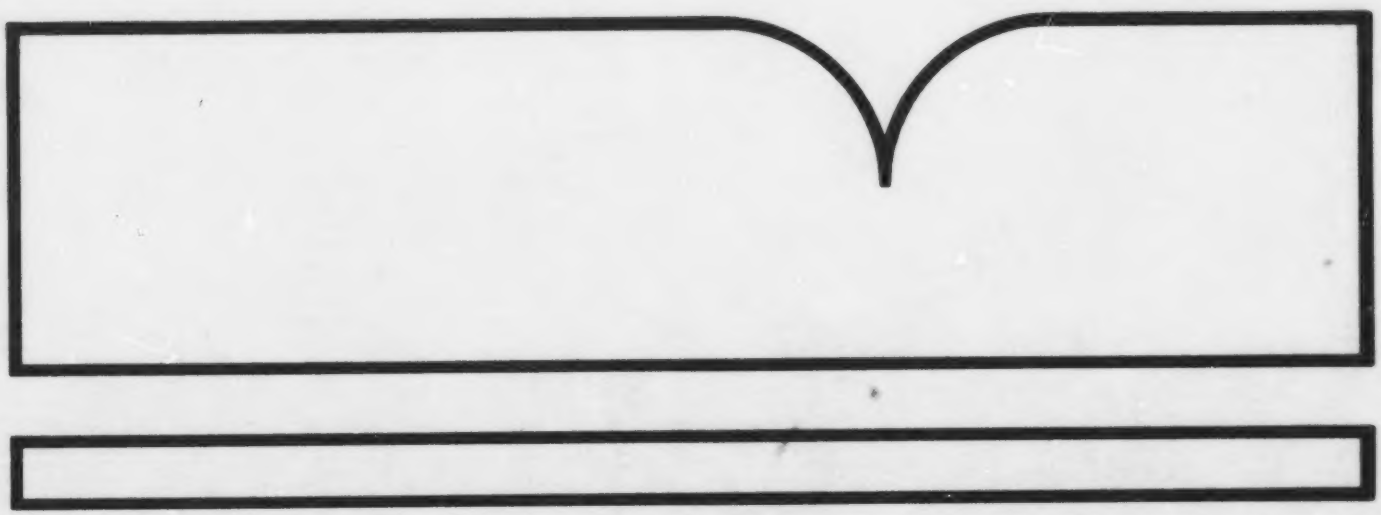

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ICE FOG ABATEMENT AND POLLUTION REDUCTION AT A SUBARCTIC COAL-FIRED HEATING PLANT

By

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16. ABSTRACT

An experimental cooler-condenser system was constructed at the coal-fired heating and electric plant on the Fairbanks campus of the University of Alaska to evaluate its potential to reduce ice fog and other pollutant stack emissions in a subarctic environment. This experiment advanced the work began by Porteous and Wallis (1965) to a stage of field evaluation for a less than full scale system. Flue gas was diverted from the existing power plant stack through the experimental system for test purposes. A cold water spray was directed into the muzzle of the experimental stack countercurrent to the direction of flue gas flow to cool the gas, condense combustion-produced water vapor and scrub the gas stream of potential pollutants before they were released to the atmosphere.

Because of several factors, the system at this stage of development proved ineffective for its main function of ice fog reduction. Some of the problems could be prevented by changes in the design of the system and some remain inconclusive and not well understood. Results show that the scrubbing function was more successful. Environmental considerations such as process water treatment and disposal presented no major obstacles, however, the potential to recover waste from the system does not appear favorable.

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ABSTRACT

An experimental cooler-condenser system was constructed at the coal-fired heating and electric plant on the Fairbanks campus of the University of Alaska to evaluate its potential to reduce ice fog and other pollutant stack emissions in a subarctic environment. This experiment advanced the work began by Porteous and Wallis (1965) to a stage of field evaluation for a less than full scale system. Flue gas was diverted from the existing power plant stack through the experimental system for test purposes. A cold water spray was directed into the muzzle of the experimental stack counter-current to the direction of flue gas flow to cool the gas, condense combustion-produced water vapor and scrub the gas stream of potential pollutants before they were released to the atmosphere.

Because of several factors, the system at this stage of development proved ineffective for its main function of ice fog reduction. Some of the problems could be prevented by changes in the design of the system and some remain inconclusive and not well understood. Results show that the scrubbing function was more successful. Environmental considerations such as process water treatment and disposal presented no major obstacles; however the potential to recover waste heat from the system does not appear favorable.

This report was submitted in fulfillment of contract #R804833-01-2 by the School of Engineering, University of Alaska, Fairbanks, Alaska, under the sponsorship of the U.S. Environmental Protection Agency.

1. BACKGROUND

Ice fog continues to be a serious environmental problem in many northern communities during winter months, not the least of which is Fairbanks, Alaska, where each year extended periods of severely cold weather (-20° to -60° F) accompanied by inversions in the adiabatic lapse rate result in a city engulfed in a dark gray haze, often limiting visibility to a few feet. The social and psychological costs of ice fog can only be qualitatively understood by those who have experienced the stress and depression of maintaining the daily routine in a fog-shrouded environment. On the other hand, the physical costs of ice fog can be calculated. Each year streets and highways become shrouded in ice fog, driving up the accident rate and taking a heavy toll in damage to property and personal injury. Poor visibility forces closures of airports and schools, and generally disrupts the local economy. But unlike other forms of fog, ice fog is not merely a meteorological phenomenon and consequence of nature which must be endured; most of the ice fog in Fairbanks is the result of man's consumption of energy within the local environment.

Ice fog has been studied and characterized by many researchers in recent years. An extremely comprehensive treatise by Benson (1970) is only one of many such works. Basically ice fog consists of minute ice crystals (less than 50 microns) suspended in the atmosphere at low temperatures when little or no suspended water vapor can be supported. Water required to form ice fog comes from three main sources:

1. Evaporation over open water (open rivers and streams, power plant cooling ponds, etc.);
2. Combustion-produced water vapor present in motor vehicle exhaust;
3. Combustion-produced water vapor present in the exhaust gases of industrial, municipal and home heating and power plants.

This report is concerned with the development of a system which could prove useful in controlling ice fog production from the third source only.

2. INTRODUCTION

The research project described in this report was concerned with the continued development of an ice fog control system which would effectively reduce ice fog emissions from coal-fired power and heating plants. Such a system was first tested by Porteous and Wallis of Thayer School of Engineering, Dartmouth College in 1965. The Porteous and Wallis experiment consisted of a model exhaust stack through which hot air was passed which had been humidified to simulate a flue gas resulting from the combustion of coal. By placing a spray nozzle at the top of this stack directed downward, counter to the direction of gas flow, a cold water spray could impact the gas stream lowering the gas temperature by a direct contact heat exchange principle to a point where combustion-produced water vapor would be condensed. The results of this work showed that (in the laboratory, at least) significant drying of the flue gas could be achieved, thus greatly reducing the potential for ice fog production. It followed that such a spray-type cooler-condenser system could also act as an effective scrubber of certain condensable and particulate contaminants which would give dual purpose to the concept. Perhaps ice fog could be reduced and stack-emitted pollutants kept within tolerable limits with a single, low-cost system precluding the need for several separate systems.

To build on the success of the Porteous and Wallis experiment we proposed the construction of a second generation system, sized at less than full scale, but using a real flue gas from an existing coal burning power plant, to be tested in an actual subarctic environment. We expected that such a field experiment would offer most of the challenges to the concept of a full size system with only a fraction of the expense. This type of model system seemed like the logical next step in the evolution of the concept. Funding was secured from the U.S. Environmental Protection Agency with a cost sharing contribution from the University of Alaska Fairbanks Physical Plant. In September of 1976 design of the experimental system began. The model system was to be built with consideration given to the potential for development of a full-scale system if the experiment proved promising.

The project continued for the next two-year period through the phases of design, construction, instrumentation, testing, data gathering and the analysis of results. The report which follows includes the conclusions drawn from this research project and recommendations for further development based on the experience of this project.

3. EXPERIMENTAL SYSTEM

3.1 General:

As stated earlier, this project intended to advance the work of Porteous and Wallis and therefore our experimental apparatus was patterned after their original system. The general method tested is illustrated in Figure 1. For this system the main control variables are:

1. Temperature of the flue gas entering;
2. Humidity of the hot gas entering;
3. Velocity of the flue gas;
4. Temperature of the cooling water;
5. Drop size of the cooling water;
6. Ratio of the mass flow rate of cooling water to the mass flow rate of flue gas;
7. The heat exchange column height (height of stack)

Since the system was to use a portion of the existing hot flue gas produced by the University power plant it was necessary to design one which would be compatible yet flexible enough to adjust operating conditions to achieve optimum results. Figure 2 shows the manner in which the experimental system was connected to the existing University power plant stack. Figure 3 shows the more specific details of the system and Table 1 lists the equipment used.

3.2 Construction:

Since the only interior access to the coal car shaker roof was by stairway up three stories from ground level, the larger pieces of equipment were set on the roof with a crane. This process began by lifting the induced draft fan and entrance section of the model stack. Then the six-foot-long stack sections were lifted onto the roof. Finally the instrumentation building, which had been prefabricated and assembled in the University's carpenter shop, was lifted and set in its desired position. The superstructure, which provided access to all levels of the stack, and the bridge structure, which provided access to the muzzle of the stack from the power plant roof also were prefabricated in the shop. The unassembled parts were then lifted by crane to the car shaker roof and final assembly was done on site. The photo (Figure 4) shows the superstructure being lifted into place.

When positioning and assembling of the major system components were complete the stack was erected by assembling the sections a piece at a time, working from the superstructure. Similarly, by working from the superstructure the stack was insulated with two inches of semi-rigid fiberglass. The photos (Figures 5 and 6) show the completed system.

Following the installation of system components the plumbing was installed. Figure 7 diagrams the mechanical system, control components and the instrumentation system as installed.

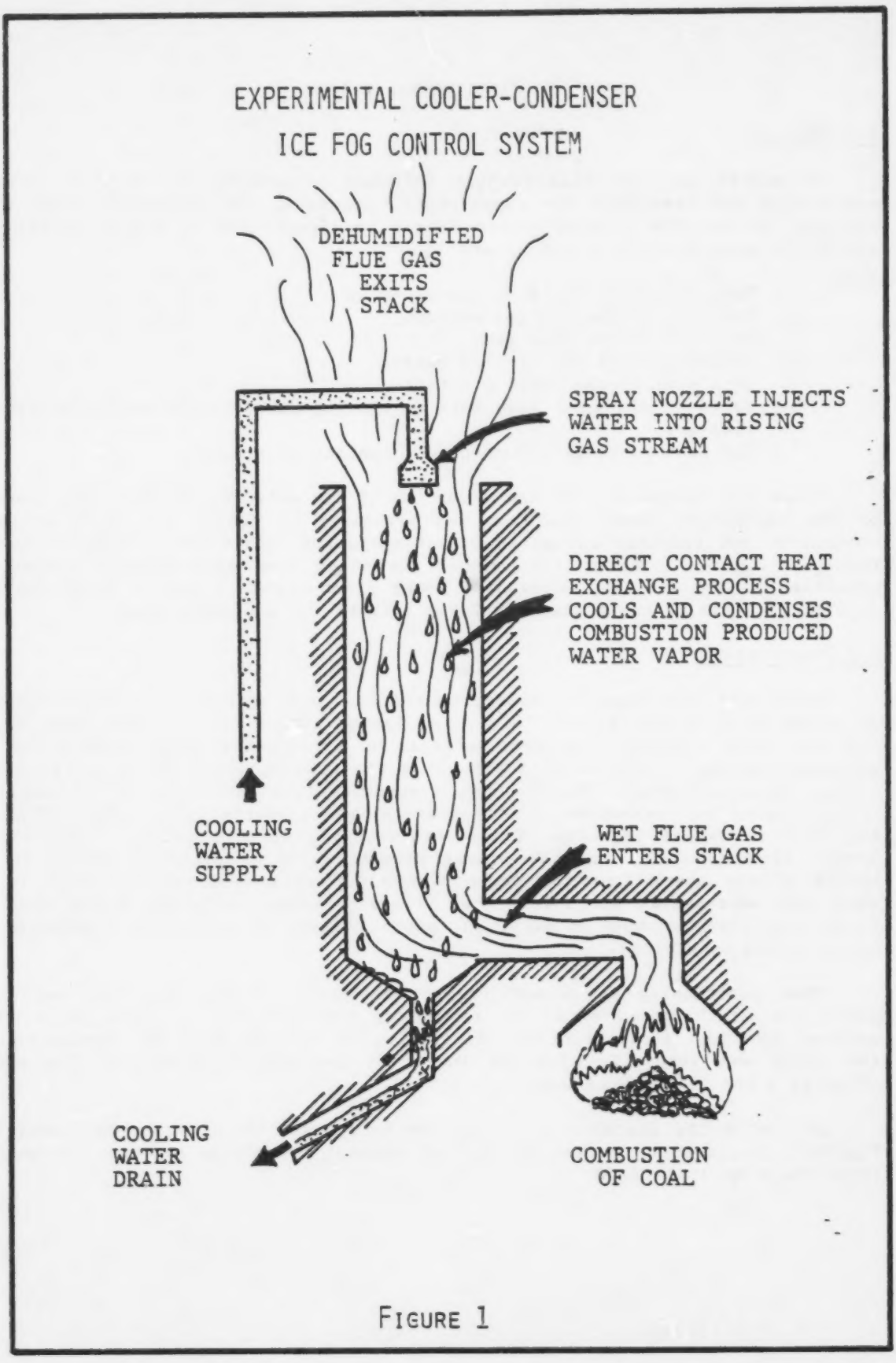
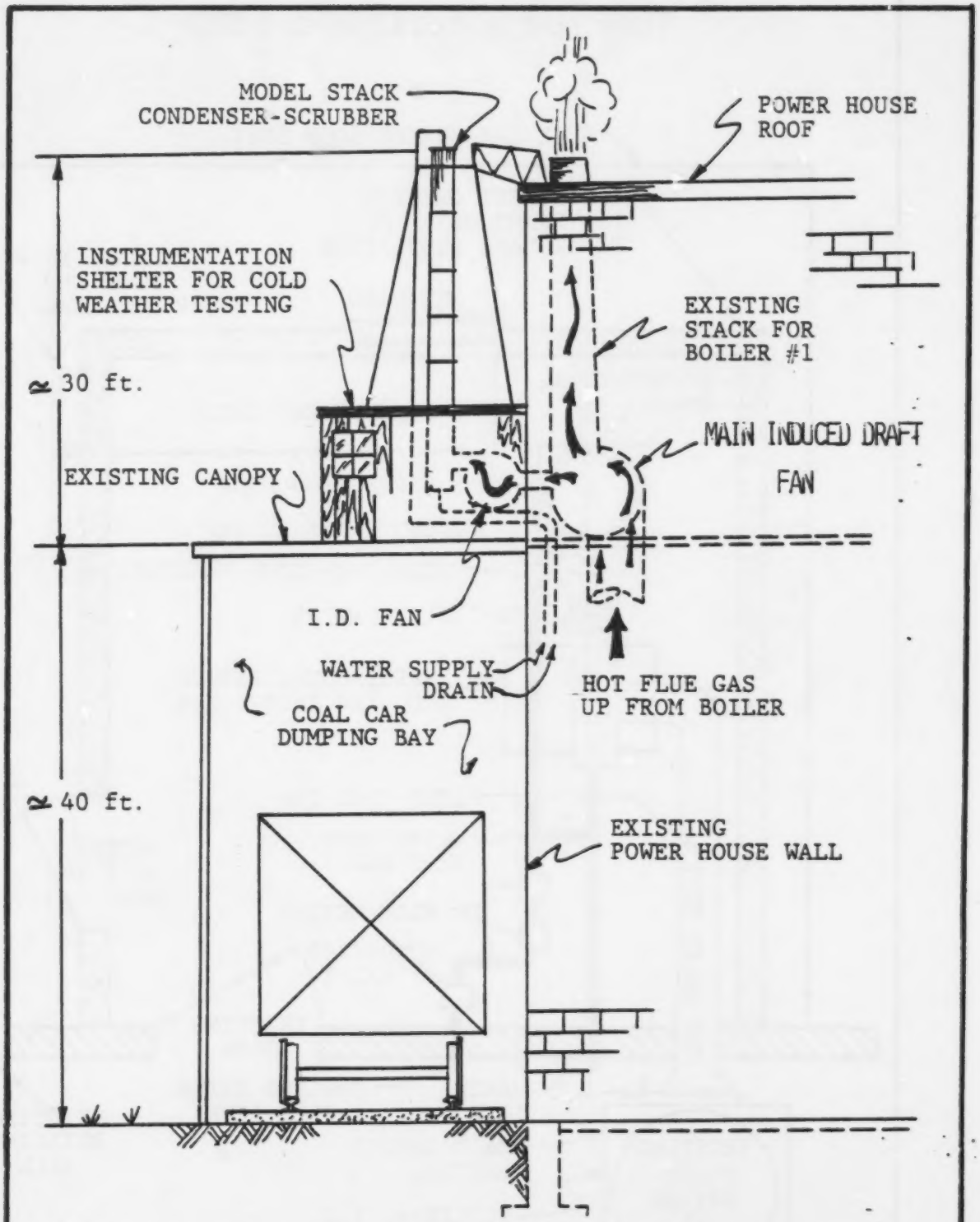

EXPERIMENTAL COOLER-CONDENSER
ICE FOG CONTROL SYSTEM
DEHUMIDIFIED FLUE GAS EXITS STACK
SPRAY NOZZLE INJECTS WATER INTO RISING GAS STREAM
DIRECT CONTACT HEAT EXCHANGE PROCESS COOLS AND CONDENSES COMBUSTION PRODUCED WATER VAPOR
COOLING WATER SUPPLY
WET FLUE GAS ENTERS STACK
COOLING WATER DRAIN
COMBUSTION OF COAL

FIGURE 1



SKETCH OF MODEL CONTROL SYSTEM AT UNIVERSITY POWER PLANT

FIGURE 2

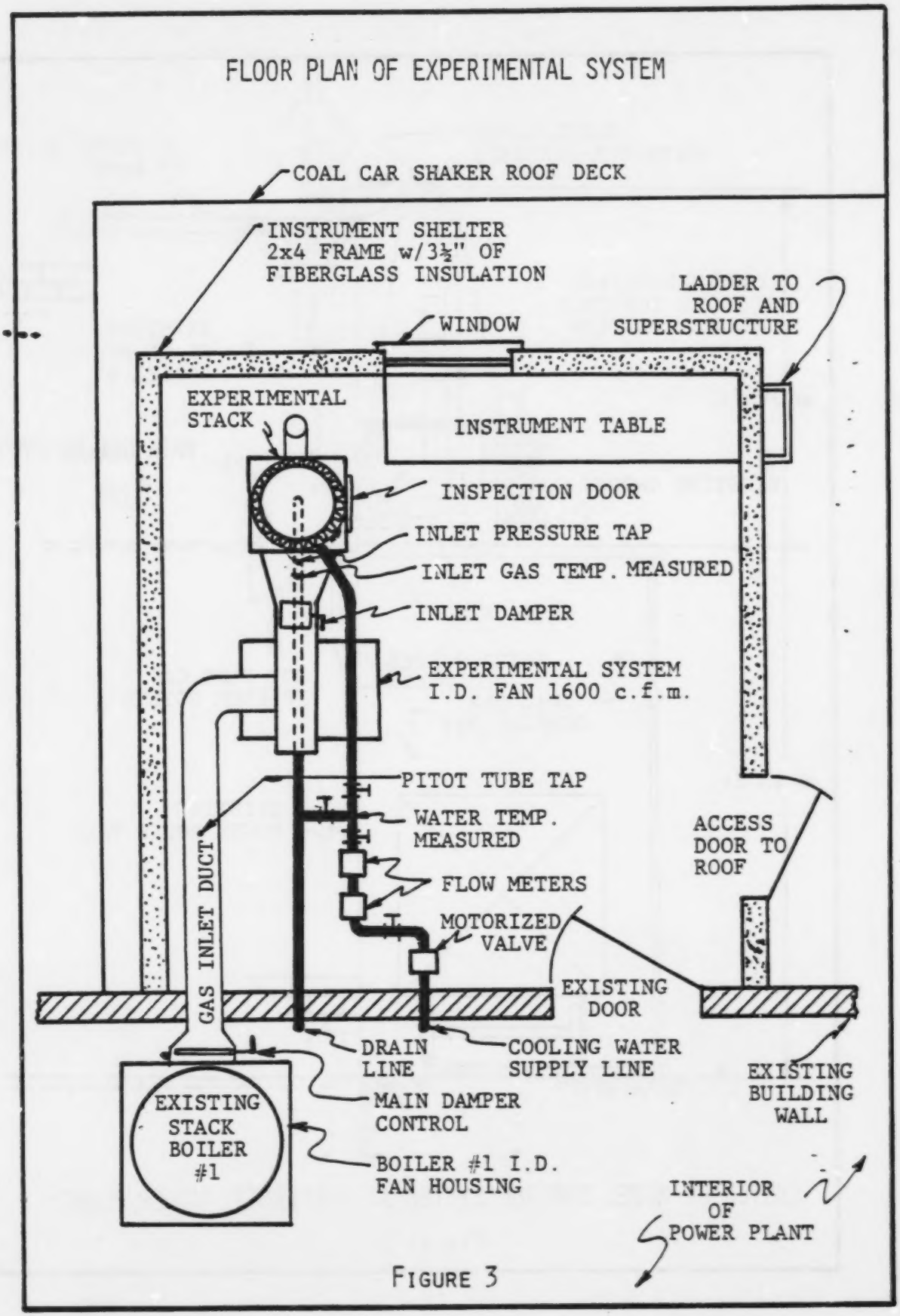
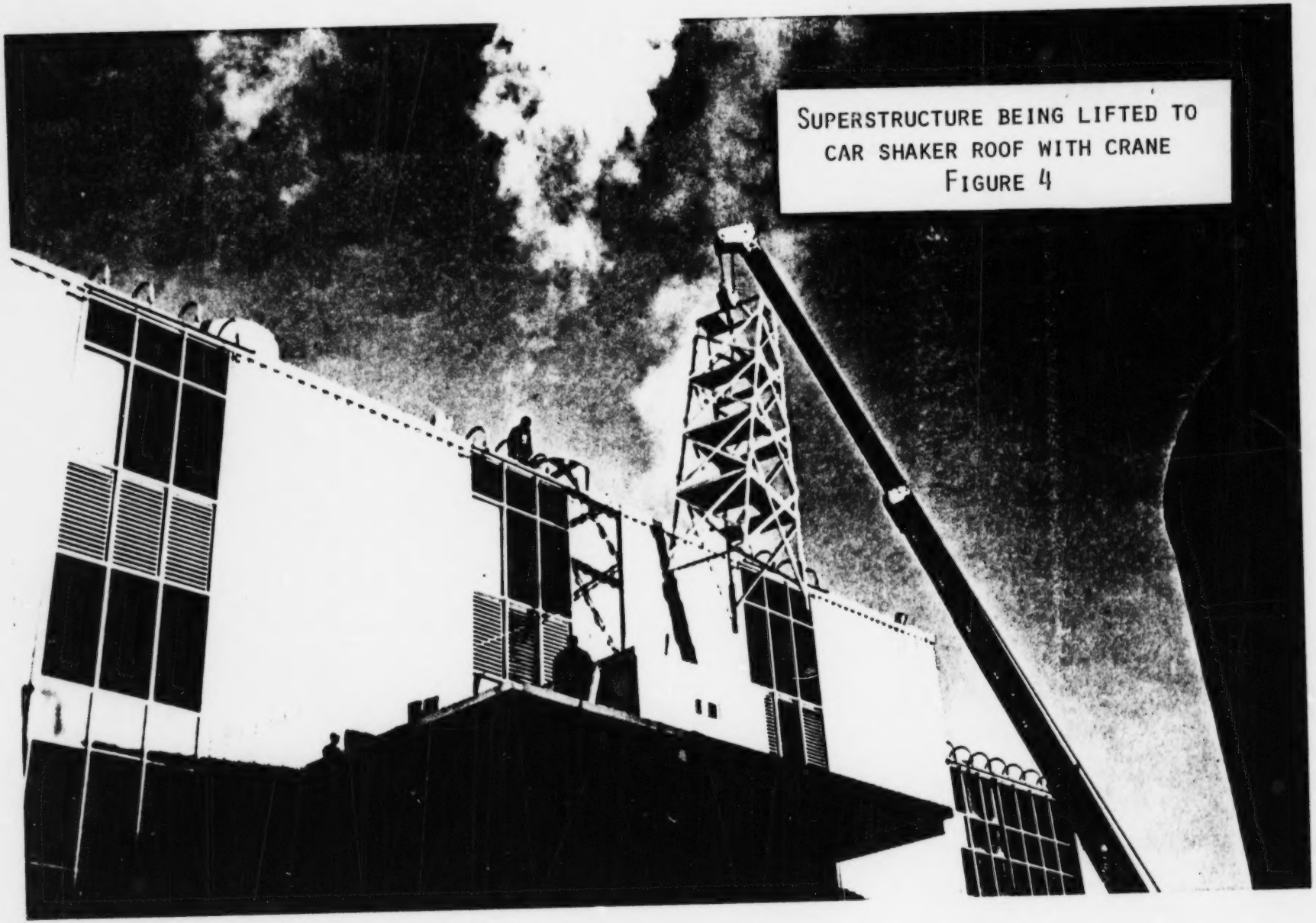

FLOOR PLAN OF EXPERIMENTAL SYSTEM
COAL CAR SHAKER ROOF DECK
INSTRUMENT SHELTER
2x4 FRAME w/3½" OF
FIBERGLASS INSULATION
WINDOW
LADDER TO
ROOF AND
SUPERSTRUCTURE
EXPERIMENTAL
STACK
INSTRUMENT TABLE
INSPECTION DOOR
INLET PRESSURE TAP
INLET GAS TEMP. MEASURED
INLET DAMPER
EXPERIMENTAL SYSTEM
I.D. FAN 1600 c.f.m.
PITOT TUBE TAP
WATER TEMP.
MEASURED
ACCESS
DOOR TO
ROOF
FLOW METERS
MOTORIZED
VALVE
GAS INLET DUCT
EXISTING
DOOR
DRAIN
LINE
COOLING WATER
SUPPLY LINE
EXISTING
BUILDING
WALL
EXISTING
STACK
BOILER
#1
MAIN DAMPER
CONTROL
BOILER #1 I.D.
FAN HOUSING
INTERIOR
OF
POWER PLANT

FIGURE 3

EQUIPMENT LIST

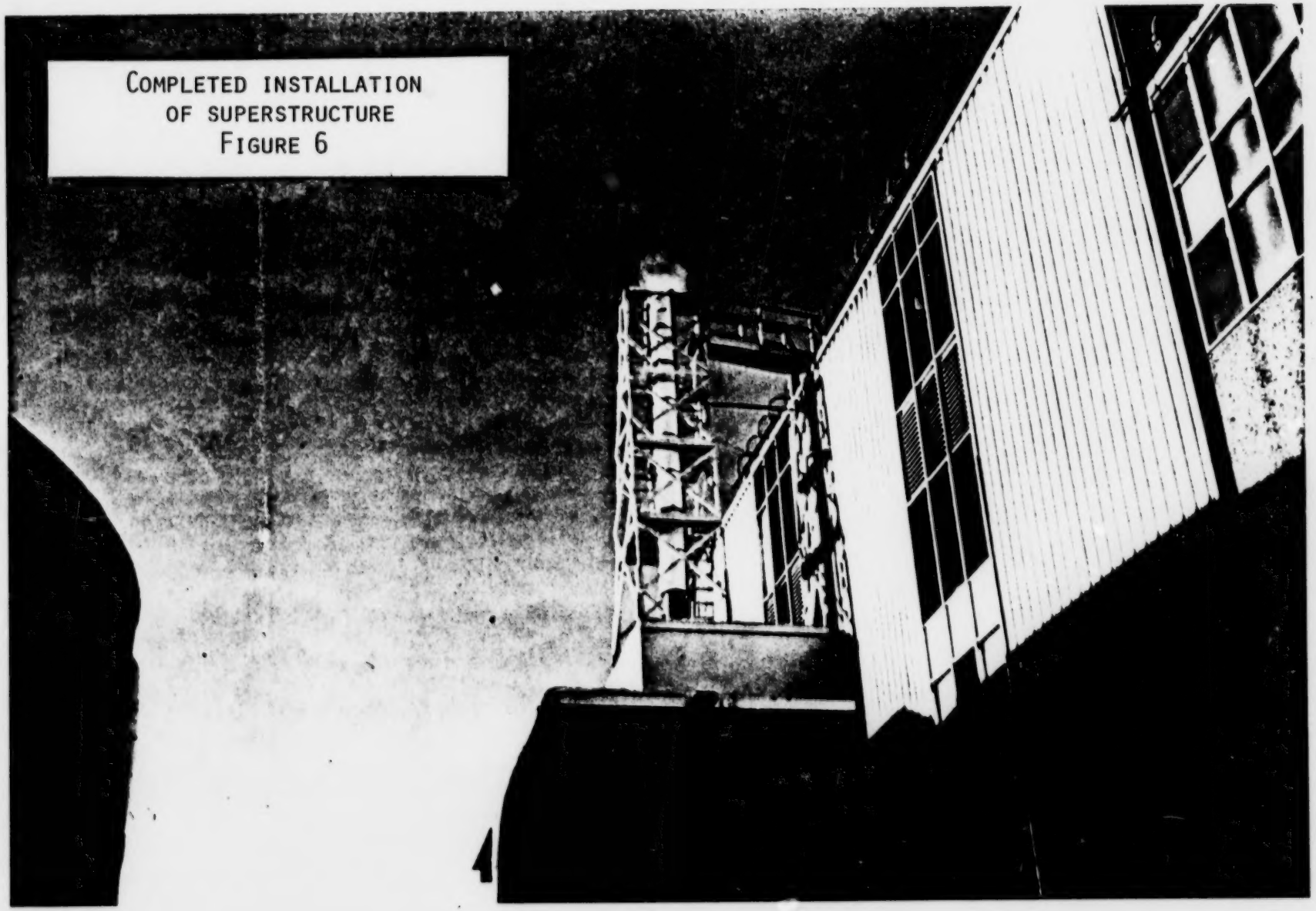
TABLE 1

1.	STACK AND ENTRANCE BASE:	Fabricated from 16 gauge mild steel
2.	INDUCED DRAFT FAN:	Barry 609 centrifugal blower 1600 c.f.m. discharge
3.	MOTORIZED EMERGENCY SHUT-OFF VALVE AND OVERFLOW SWITCH:	Honeywell Inc. 2" motorized valve with model 3N2B Warrack probe assembly
4.	FLOW METERS:	17351 86S Rotameter 17351 95S Rotameter
5.	PITOT TUBE:	Dwyer model 160-24P
6.	MANOMETERS:	Dwyer Instruments Inc. (1) model 421-5 inclined (1) model 246ST inclined
7.	THERMOCOUPLE THERMOMETER:	Omega Engineering, Inc. Model 200 Digital
8.	HUMIDITY INSTRUMENT:	Foxboro Dew Cell 2711 and Power Supply 2712
9.	PARTICULATE SAMPLER:	See section 6.2, "Particulate Sampling"

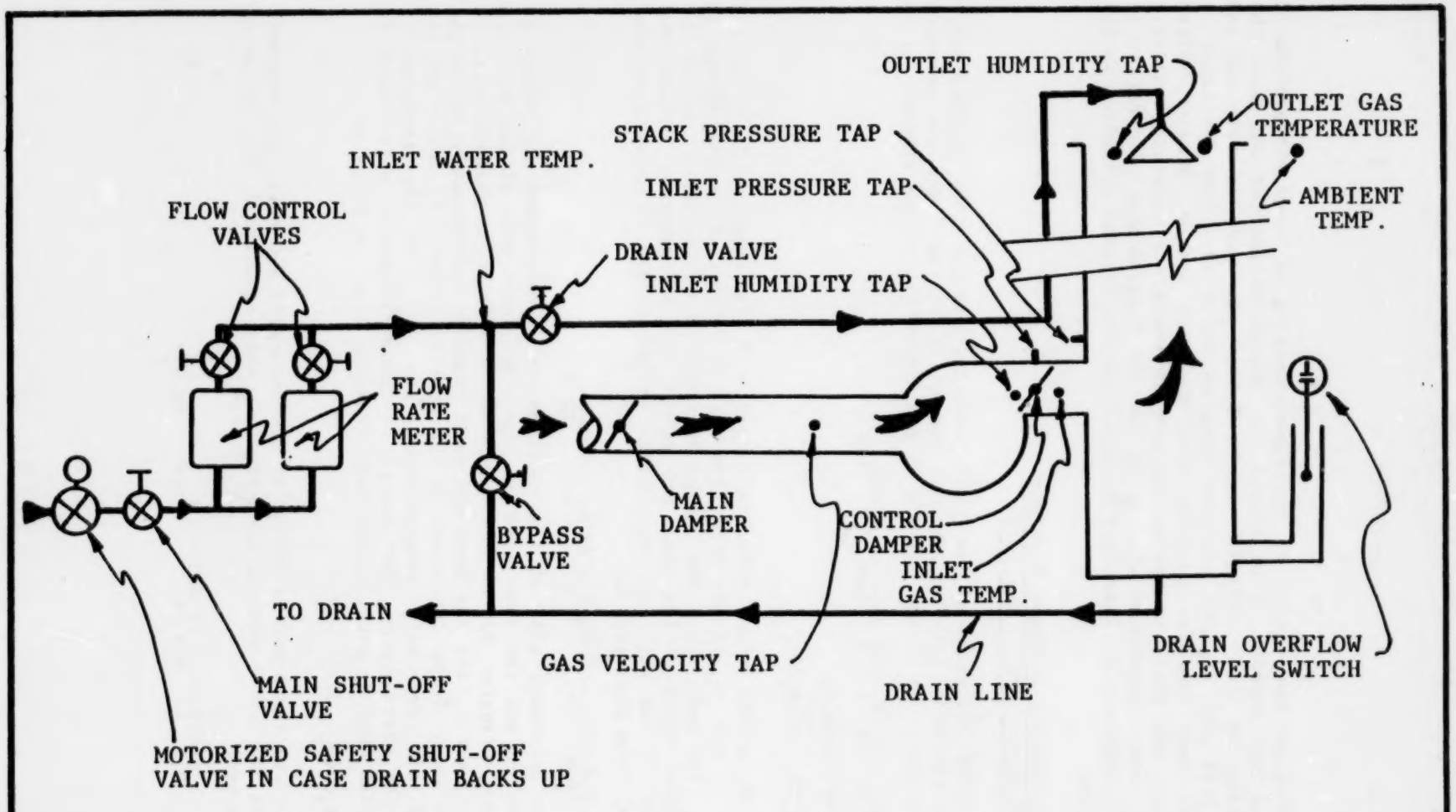


SUPERSTRUCTURE BEING LIFTED TO CAR SHAKER ROOF WITH CRANE
FIGURE 4

COMPLETED INSTALLATION
OF SUPERSTRUCTURE
FIGURE 5



COMPLETED INSTALLATION
OF SUPERSTRUCTURE
FIGURE 6



SCHEMATIC OF EXPERIMENTAL SYSTEM

FIGURE 7

4. THEORY

4.1 General:

In this section the theory of cooling-condensing of combustion-produced water vapor and its removal is developed. It should be pointed out that the original intention in this analysis was to follow the work of Porteous and Wallis and utilize the digital computer program which they had developed to solve the basic heat transfer problem posed by this system. However, after numerous attempts, the Porteous and Wallis program would not generate realistic results. It was never determined whether or not the program was in error or if we were using it improperly. Therefore we developed the program discussed in the following sections.

4.2 Counter Flow Contact of Moist Flue Gas with Chilled Spray Water - Analysis:

Figure 8 shows a diagram of the stack with the counter flow chilled water spray. Ignoring the heat transfer through the walls of the tower and assuming steady flow conditions, an energy balance on a differential volume element yields

$$m_a dh = - \left[m_w - m_a(W_2 - W) \right] dh_{f,w} + m_a dW h_{f,w} \qquad (1)$$

which can be simplified to

$$m_a dh = - m_w dh_{f,w} + m_a dW h_{f,w} \qquad (2)$$

by neglecting the second order terms in equation 1. In equation 2, m_a is the mass flow rate of gas, m_w is the mass flow rate of water, dh is the change in enthalpy of the flue gas, $dh_{f,w}$ the change in enthalpy of the water, and dW the change in humidity ratio of the flue gas across the differential volume. The change in energy of the water in the control volume is due to convective heat and mass transfer from the drops or

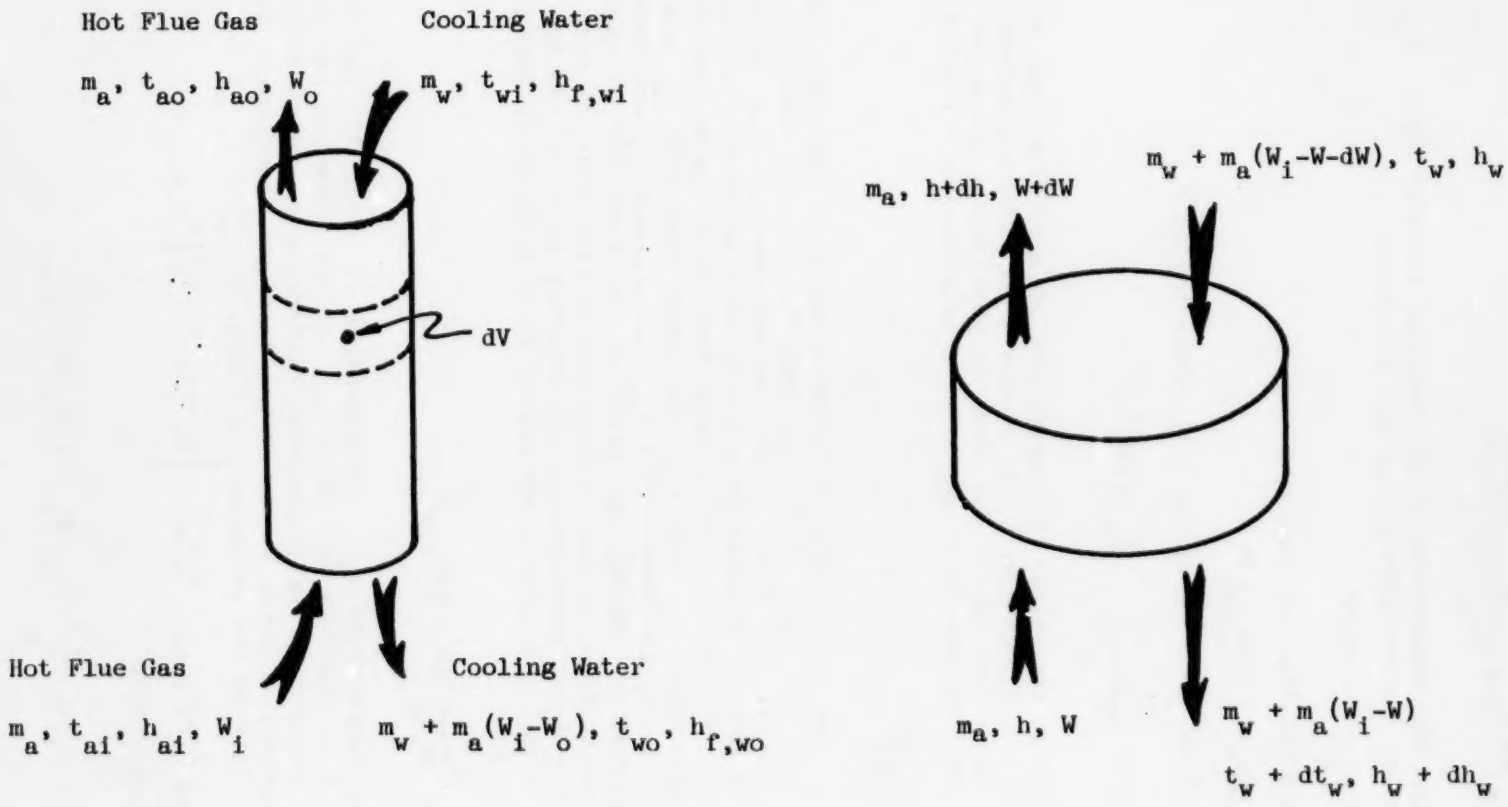
$$-m_w dh_{f,w} = h_c A_v dV(t_w - t) + \rho h_d A_v dV(W_{s,w} - W) h_{fg,w} \qquad (3)$$

The term on the left-hand side of the equation above represents the change in energy of the water and the two terms on the right-hand side of the equation represent the heat transfer due to convection and evaporation, respectively. In this equation, h_c and h_d are the heat and mass transfer coefficients, A_v is the surface area of water drops contained in the control volume, t_w and t are the water drop and air dry bulb temperatures, and $h_{fg,w}$ is the enthalpy of evaporation of the water spray. The change in concentration of water vapor in the flue gas stream must be equal to the mass transfer from the drops or

$$m_a dW = \rho h_d A_v dV(W_{s,w} - W) \qquad (4)$$

where $W_{s,w}$ and W are the humidity ratios of the saturated and moist gas streams. Upon substituting the Lewis number, $Le = h_c / h_d C_{p,a}$ into equation 3, the following equation is obtained

$$-m_w dh_{f,w} = \rho h_d A_v dV \left[Le C_{p,a}(t_w - t) + (W_{s,w} - W) h_{fg,w} \right] \qquad (5)$$



SCHEMATIC DIAGRAM OF COUNTER-FLOW SPRAY DEHUMIDIFIER AND ENERGY-MASS BALANCE ACROSS A DIFFERENTIAL ELEMENT

FIGURE 8

Substituting equations 2 and 4 into equation 5 and rearranging yields

$$\frac{dh}{dW} = Le\ C_{p,a}\ \frac{(t_w - t)}{(W_{s,w} - W)} + h_{g,w} \tag{6}$$

Now using the approximation of constant specific heat, $C_{p,a}$, in the defining equation for the enthalpy of the gas stream, or

$$h = C_{p,a}t + 1061W \tag{7}$$

equation 6 can then be rewritten as

$$C_{p,a}(t_w - t) = (h_{s,w} - W) \tag{8}$$

Equation 8 is now substituted into equation 6 to yield

$$\frac{dh}{dW} = Le\ \frac{(h_{s,w} - h)}{(W_{s,w} - W)} + (h_{g,w} - 1061Le) \tag{9}$$

This equation represents the operating or condition line on the psychrometric chart for the changes in state as the moist flue gas passes through the stack. Although data for the Le for counter flow stack operation are not available, Kusuda (1965) recommends an approximate relationship for air flow as

$$Le \cong \left(\frac{\alpha}{D}\right)^{2/3} \tag{10}$$

where α is the air thermal diffusivity and D is the water vapor diffusivity in air. Thermal and vapor diffusity data for dry and saturated moist air can be found in Eckert and Drake (1959). An accurate although approximate solution to equation 8 can be obtained graphically on a psychrometric chart. For one set of operating conditions for the counter flow stack assume the entering and leaving water temperatures t_{wi} and t_{wo}, the water flow rate m_w, and the gas-flow rate m_a, and entering gas temperature t_{ao} and pressure p_a are known. Then equation 9 can be solved for dh/dW, the slope of the condition or operating line on the psychrometric chart. A line segment having this slope is then drawn on the chart through the point representing the entering state of the hot flue gas. A short distance along this line a new state "1" is arbitrarily located. Then, rewriting equation 2 as

$$\Delta t_w = -\frac{m_a}{m_w C_w}(\Delta h - \Delta W h_{f,w}) \tag{11}$$

the water temperature $t_{w,1}$ corresponding to state "1" can be calculated. Next equation 9 is resolved for $(dh/dW)_{"1"}$ and the procedure repeated until the final flue gas temperature is determined. Performing an energy balance for the entire stack provides a check on the final flue gas temperature determined from the condition line on the psychrometric chart, or

$$m_a h_{ai} + m_w h_{f,wi} = m_a h_{ao} + \left[m_w - m_a(W_o - W_i)\right] h_{f,wo} \tag{12}$$

Rearranging yields

$$h_{ao} = h_{ai} + \frac{m_w C_w}{m_a}(t_{wi} - t_{wo}) + (W_o - W_i)h_{f,wo} \tag{13}$$

If the outlet flue gas temperature has been determined and the average mass transfer coefficient, $h_d A_v$, is known, then the volume of the stack may be obtained from

$$V = \frac{m_a}{h_d A_v} \int_{W_i}^{W_o} \frac{dW}{W_{s,w} - W} \tag{14}$$

The above integral can be solved by numerical or graphical techniques.

For this study, a computer program was written (Appendix A) to calculate exit gas temperature and humidity ratio, exit water temperature, and percent moisture removed based on the foregoing analysis and the following calculation procedure.

The input variables to the computer program are the entering gas temperature, humidity ratio and velocity, the entering water temperature, drop size and velocity, flow ratio (ratio of water flow rate to air flow rate) and stack height. The program begins by assuming an exit water temperature at the bottom of the stack. Then based on the given entering gas conditions and this assumed leaving water temperature, the saturation humidity, thermal diffusivity, viscous diffusivity, mass diffusivity, and thermal conductivity are calculated at these conditions according to the following formulas:

$$W_{s,w} = .001276e^{3.539(t_W - 460)} \quad [\text{lbw/lba}] \tag{15}$$

$$\alpha = .0001568 + 9.4894 \times 10^{-7} T_a \quad [\text{Ft}^2/\text{Sec}] \tag{16}$$

$$\nu = .0001147 + 6.28 \times 10^{-7} T_a \quad [\text{Ft}^2/\text{Sec}] \tag{17}$$

$$\underline{D} = 2.397 \times 10^{-4} \left(\frac{T_a + 460}{460}^{1.81} \right) \quad [\text{Ft}^2/\text{Sec}] \tag{18}$$

$$k = 3.7339 \times 10^{-6} + 6.3011 \times 10^{-9} T_a \quad [\text{Btu/sec-ft-F}^\circ] \tag{19}$$

These equations were developed using a linear least squares fit of property data given in Ozisik (1977) for α, ν, and k; and ASHRAE (1977) for $W_{s,w}$. The mass diffusivity relationship is given in Eckert and Drake (1959).

To calculate the heat and mass transfer coefficients for the water drops, required for equations 4 and 9, the Prandtl, Pr, Schmidt, Sc, and Reynolds, Re, numbers are required and calculated based on the previously defined property data. These moduli are

$$Pr = \nu/\alpha \tag{20}$$

$$Sc = \nu/\underline{D} \tag{21}$$

$$Re = \frac{Vd}{\nu} \tag{22}$$

where V and d in the Reynolds number represent the relative velocity between the drops and gas and diameter of the drops, respectively. The Nusselt number, Nu,

for heat transfer and Sherwood number, Sh, for mass transfer can now be calculated according to Ranz (1952) as

$$Nu = \frac{h_c d}{k} = 2.0 + .6Re^{\frac{1}{2}}Pr^{1/3} \tag{23}$$

$$Sh = \frac{h_d d}{D} = 2 + .6Re^{\frac{1}{2}}Sc^{1/3} \tag{24}$$

At this point, W across the differential element can be calculated according to equation 4. Then using this value, h for the gas stream can be determined using equation 9. Finally, t_w can be found using equation 11. The humidity ratio, gas stream enthalpy, and water temperature are then incremented to determine the conditions on the other side of the differential element. These conditions become the initial conditions for the second element as the process is continued step by step up the stack. When the top of the stack is reached, the calculated water temperature is compared to the given entering water temperature and the initial guess of exit water temperature is adjusted either up or down and the process repeated until the desired accuracy is achieved.

5. TESTING

5.1 Narrative:

The experimental system was 95% constructed by December 15, 1976. However, several essential components did not arrive until the first week of January 1977. When all equipment was installed the system was tested to insure all components were working satisfactorily and everything seemed to be in good working order. The intention at this point was to wait for a period of ice fog conditions (ambient temperatures of less than $-15^{\circ}F$) to begin the operational testing.

Fortunately for the residents of Fairbanks, but rather distressing for the conduct of this project, January 1977 proved to be one of the warmest on record for interior Alaska. Several local temperature readings were recorded in the $+40^{\circ}F$ range and the month passed with no opportunity to test the system. February weather was similar with few cold days and the rapid changes in the weather resulted in many wasted hours for the project staff.

A typical occasion would find the temperatures dropping below the $0^{\circ}F$ level and plans would be made to assemble the staff for testing to begin the next morning. All personnel would then arrive on the scene only to find the temperature rising with the sun and a new daily record high was in the making.

This scenario continued throughout the winter and it was finally concluded that there would be no opportunity to test the system under ice fog conditions during the remainder of the 1977 season. In March it was decided to apply for a "no cost to project" one-year contract extension. In this manner the testing could be suspended until the next winter (1977-1978). The request to the Environmental Protection Agency for extension was made and approved and all work on the project was temporarily suspended.

In November of 1977 project personnel prepared to ready the system for winter testing. However, while the system had been unattended the hot flue gas, carrying with it an abrasive fly ash, had eroded the plate in the main control damper (shown in Figures 3 and 7) which acted as a disconnect valve shutting off the experimental system from the main stack. Since the damper and housing could not be removed while the main boiler was running; and since the power plant operation could not be interrupted for the sake of our project, it was not possible to assess the degree of erosion damage.

During the unattended period the amount of hot flue gas leakage past the damper had steadily increased as the plate erosion worsened. This small but steady flow of gas carried with it a surprising amount of fly ash. Since the normal course for the gas to follow once inside the ducting of the experimental system was into and up the stack, and since the flow rate was very low without the induced draft fan running, the stack gas velocity was also low. This caused the heavier particles of fly ash (appearing to be mostly mineral ash) to precipitate out of the gas stream and collect in the drain reservoir and in the stack entrance section. The lighter particles (which appeared to be mostly carbon soots) continued up the stack with the gas, but collected on all metal parts near the stack outlet where condensation provided a damp, sticking surface. Figure 8 is a photograph of the deposits collected at the stack outlet.

The mixture of soot- and combustion-produced condensables resulted in severe corrosion of several instruments:

1. The isokinetic gas sampling probe located at the muzzle of the stack was badly corroded and all sampling orifices were plugged.
2. The Dew Cell probe which measured humidity of the gas at the stack outlet was badly corroded and we were never able to record an intelligible reading from it again. Since replacement required 90 days lead time it was decided to continue without humidity monitoring.
3. The thermocouple string at the outlet of the stack had to be replaced.

The refurbishing and cleaning of the system required several days and it was not until the first week of December 1977 that the system was finally ready for operation. But when the system was tested it was found that the humidity sensors at both the inlet and outlet of the stack would not produce coherent readings. All other instrumentation seemed to be functioning properly.

Suitable ice fog conditions occurred in mid-December 1977. However, the outside door of the instrument hut had been inadvertently left ajar and the night before testing was scheduled to begin, the door blew open. When we arrived to begin testing we found the entire cold water supply system had frozen. Pipes were broken and, most critical, the glass tubes in the flow meters were shattered.

Since no meaningful tests could be run without knowing the flow rate of the cooling water, we suspended operation until the damage could be repaired. Special order of replacement parts for the flow meters was required, thus the system was not operational until January 1978. At that time it was determined that testing could no longer be delayed, in spite of the less than ideal ambient temperatures. On January 13, 1978 operational testing was begun and continued until March 2, 1978.

5.2 Results:

Operational tests were run periodically. There was only one day during the test period when near ice fog conditions occurred. This was February 2 when the ambient temperature was $-15^{\circ}F$. All of the other tests were performed at temperatures well above $0^{\circ}F$. The data obtained during testing with respect to the mechanical parameters of the system are listed in Appendix C.

5.3 Test Procedure:

The testing procedure is described as follows:

1. Upon arrival on site the stack was visually inspected to assure everything was in proper working order and all water drains were clear (often precipitated fly ash had to be removed from the cooling water drain before proceeding).
2. The system dampers were opened and the induced draft fan turned on to dry out the system and blow out any accumulated fly ash.
3. During the dry run system parameters were usually recorded and the cooling water flow rate was designated as 0.

4. Dampers were set to the desired position for the test.
5. Cooling water was turned on and the desired rate of flow was set.
6. System parameters were then observed and when a steady state condition was reached the data were recorded.
7. The cooling water flow rate was then set at a new incremental step and parameters again observed until steady-state occurred and the data were recorded. This process was followed through successive incremental cooling water flow rates until the available range of flow rates were observed.
8. During some of the tests gas samples were taken to measure particulate scrubbing performance. Water samples were also taken for analysis of necessary treatment procedures which might be required in a full-scale operational system as well as to determine the degree of contaminant scrubbing that was occurring as a result of the gas/water interaction. Both gas and water sampling procedures are discussed in detail in later sections of this report.

5.4 Observations of the Mechanical System:

The following is a discussion of qualitative observations made while testing the functional response of the mechanical system. The detailed quantitative discussion is presented in the Analysis of Results section.

5.4.1 Water Removal:

The major intent of the experiment was to demonstrate a method of removing combustion-produced water vapor from flue gas, thus reducing ice fog produced during cold temperatures. Since ice fog is a visual form of pollution similar to other fogs, the measure of success is largely qualitative. If it is obvious that the size of the vapor plume emitted from the stack is significantly reduced, then the main goal has been achieved. The quantitative evaluation becomes the measure of the actual percentage of total water vapor removed.

In this project at no time during testing was a reduction in the vapor plume observed by cooling the flue gas with the water injection system. Even though little testing occurred during ice fog conditions, the general observation of no apparent reduction in the vapor plume leads to the conclusion that the main goal of the project was not attained. Since the theory has shown that water removal is possible and since Porteous and Wallis have successfully demonstrated the technique in the laboratory, the major emphasis of the project shifted to an analysis of why the system was not performing as expected.

With respect to combustion-produced water vapor removal, several problems associated with the system were observed which could not be corrected.

5.4.2 Entrainment:

It was observed in early testing that rather than reducing plume size the plume often increased when water injection began. This phenomenon could only be caused by an addition of water to the system. And the only source of additional water was the cooling water injected into the gas stream. It was concluded that cooling water was being entrained in the gas stream and carried over the stack outlet. This was confirmed on January 19 when it was observed that following the

tests all automobiles parked in the immediate vicinity of the power plant were covered with a thin glaze of ice at a time when no other precipitation was observed in any other area about the University campus. Precipitation of entrained water was also felt as a mist on one's face when standing below the stack and looking upward.

Entrainment occurs when:

1. The terminal velocity of the falling spray droplet is less than the upward velocity of the flue gas.
2. The droplets are unstable in their formation such that shattering of the droplet occurs while falling through the upwardly directed gas stream or impacting against an obstruction during the fall. When shattering occurs lightweight water particles become entrained and are carried over the stack outlet.

The two variables controlling the entrainment problem are the flue gas velocity and the design of the gas ducting system.

5.4.3 Stack Gas Velocity:

In the experimental system the stack gas velocity was controlled by the position of the main damper (see Figure 7). The inlet damper served as a secondary control or fine adjustment of the gas flow. During the first winter following construction (1976-1977) the velocity control seemed fairly positive. By closing the main damper by degree the stack gas velocity could be adjusted from around 15 feet per second down to approximately 3 feet per second. This range was similar to that used by Porteous and Wallis (1965), in their experiments. During the second winter, after the particulate matter in the flue gas had eroded the main damper, close velocity control was not as easily achieved; but the operational tests stack velocities ranged from 5.5 to 13.2 feet per second, which would have been well below the threshold needed to create a negative drop velocity and thus cause entrainment directly.

This observation suggested that the entrainment was being caused by some indirect effect independent of the gas-water velocity relationship. In the original testing performed by Porteous and Wallis (1965) ntrainment had been caused by a defective spray nozzle. This was overcome by the replacement of the nozzle.

5.4.4 Nozzle Design:

A diagram of the spray nozzle used is shown in Figure 9. It is similar to the type used by Porteous and Wallis (1965) and had an interchangeable orifice plate. The orifice plate designated as "A" in Figure 9 was used for all tests through February 2. While trying to explain why entrainment of water was continuing we noticed that the spray pattern was holding to the center of the gas column as shown in Figure 10(A). We believed since we were not getting a uniform spray distribution across the entire cross section of the stack that the velocity of the gas near the center of the stack was being reduced by the impact of the spray, and perhaps this was causing an acceleration of the gas near the stack walls which was resulting in high enough gas velocities that entrainment and carryover of water was resulting.

We redesigned the orifice plate as shown in Figure 9(b) and began tests with the new plate on February 21. The new plate resulted in an improved spray pattern which appeared to cause a uniform spray over the full cross section of the stack as shown in Figure 10(B). However, this did not stop the carryover of water.

With respect to the droplet formed by this nozzle design we observed a uniform pattern. We could not detect any distortion of the droplets near the point of injection. We could not observe any droplet shattering near the stack outlet. It was obvious however, that at the bottom of the stack, where the spray terminated impacting the drain reservoir and stack gas entrance housing, that the droplets were fracturing on impact and causing an atomized mist to form, much like that observed a few inches above the hood of an automobile while parked during a heavy thunder shower.

Because of the observed high quality of spray pattern and droplet shape near the stack outlet we have assumed that this entrainment problem begins near the bottom of the stack and terminus of the spray water droplets. Droplet fragments and aerosols resulting from the destruction of the falling droplets upon impacting the enclosure are borne upward, entrained in the gas stream and eventually carried past the stack outlet. Had we the opportunity to experiment further with various shapes of reservoir and drain sections perhaps this problem could have been eliminated. The sketch in Figure 11 suggests how the problem results and how improved design might eliminate the problem.

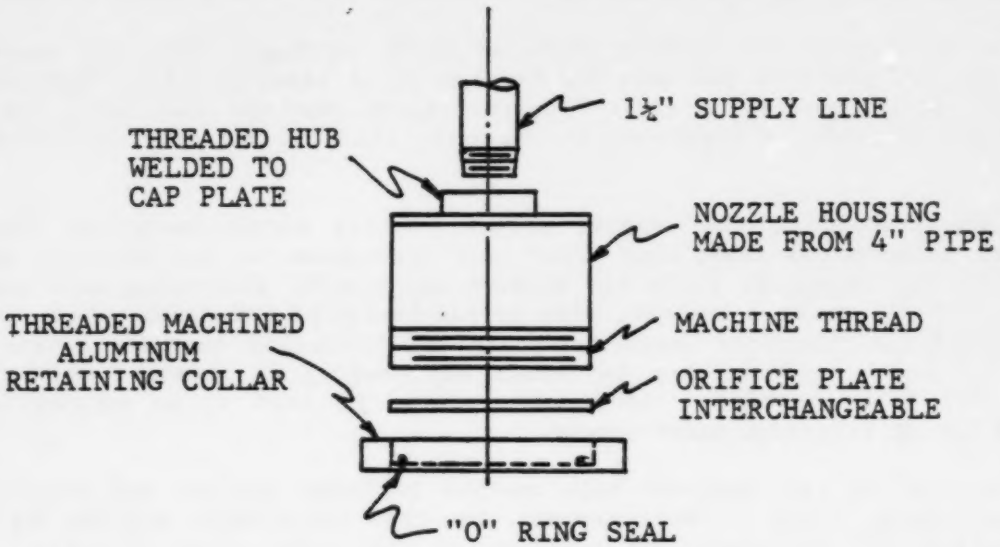
5.4.5 De-misters:

One potential solution to controlling the emission of entrained water would be to place a screen or filter-like device over the stack outlet which would act as a nucleation site for the water particles causing coalescing which would eventually drain water droplets back down into the stack when they reached a size sufficient for gravity to apply the necessary force. This technique was successfully used by Coutts (1978) in his work when eliminating ice fog produced by automobiles using the cooler-condenser principle.

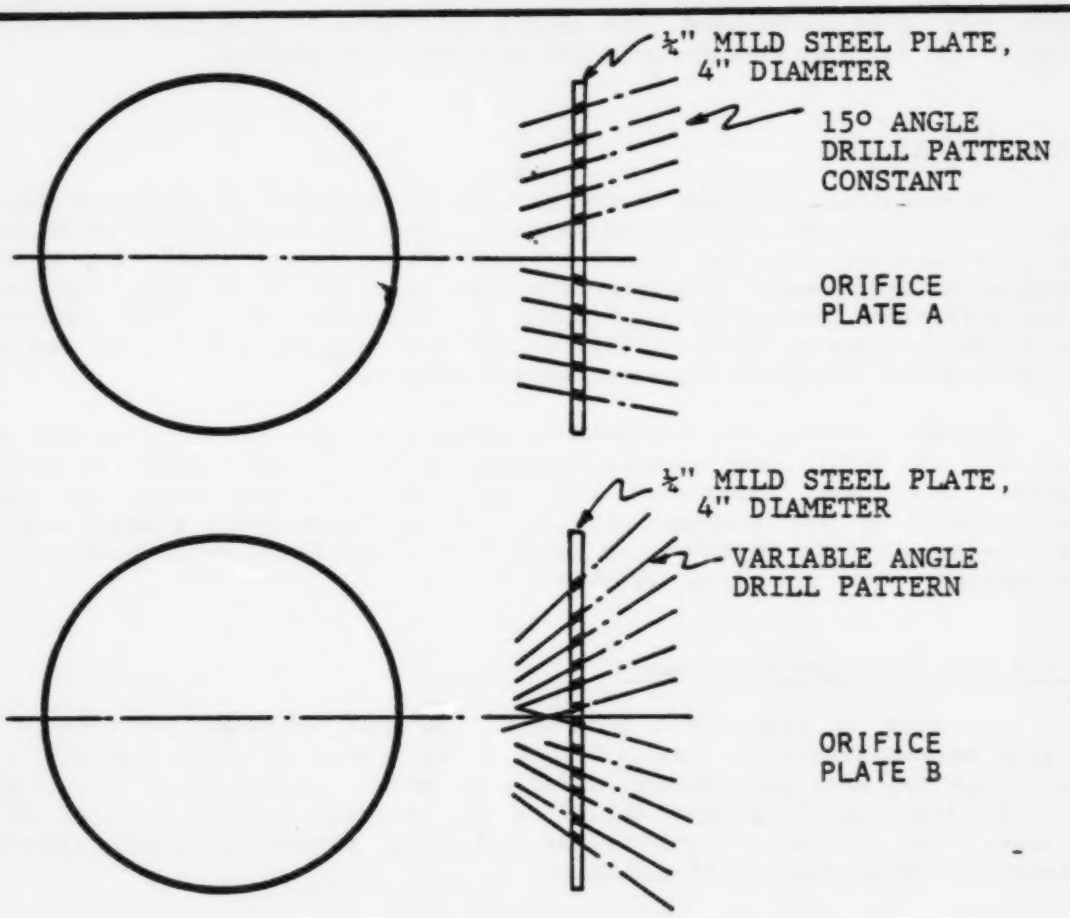
However, unlike the automobile exhaust or the pseudo flue gas used by Porteous and Wallis, our exhaust contained a considerable amount of particulate matter. Since our experience had been that the combination of water and particulate fly ash produced a glue-like substance which plugged every small orifice on which it impacted, we decided that the de-mister apparatus would not be appropriate or provide a workable solution.

5.4.6 Heat Exchanger Performance:

The data in Appendix C show that the heat exchange performance of the system worked reasonably well. Figure 12 is a plot of stack gas exit temperatures (in log mean temperature difference) versus cooling water flow rate. This will be discussed in greater detail in the analysis section. In this section we discuss the limitation of various operating parameters which affected the observed heat exchange performance.



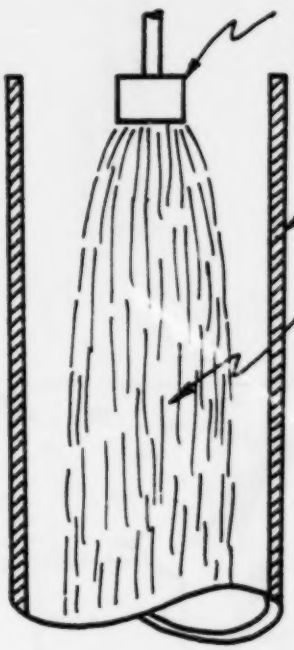
EXPLODED VIEW OF NOZZLE



NOZZLE DETAILS

FIGURE 9

CHARACTERISTICS OF SPRAY NOZZLE DESIGN


SPRAY NOZZLE USING ORIFICE PLATE SHOWN IN FIGURE 9(A)
EXHAUST STACK
COOLING WATER SPRAY PATTERN--NOTE THAT SPRAY IS CONCENTRATED TOWARD THE CENTRAL PORTION OF THE STACK SECTION

SPRAY PATTERN OBSERVED DURING TESTING FROM 1-18-78 to 2-8-78

FIGURE 10(A)

SPRAY NOZZLE USING ORIFICE PLATE SHOWN IN FIGURE 9(B)
EXHAUST STACK
COOLING WATER SPRAY PATTERN--NOTE THAT PATTERN IS SPREAD ACROSS THE TOTAL CROSS SECTION OF STACK

SPRAY PATTERN OBSERVED FROM 2-21-78 UNTIL TESTING ENDED 3-2-78

FIGURE 10(B)

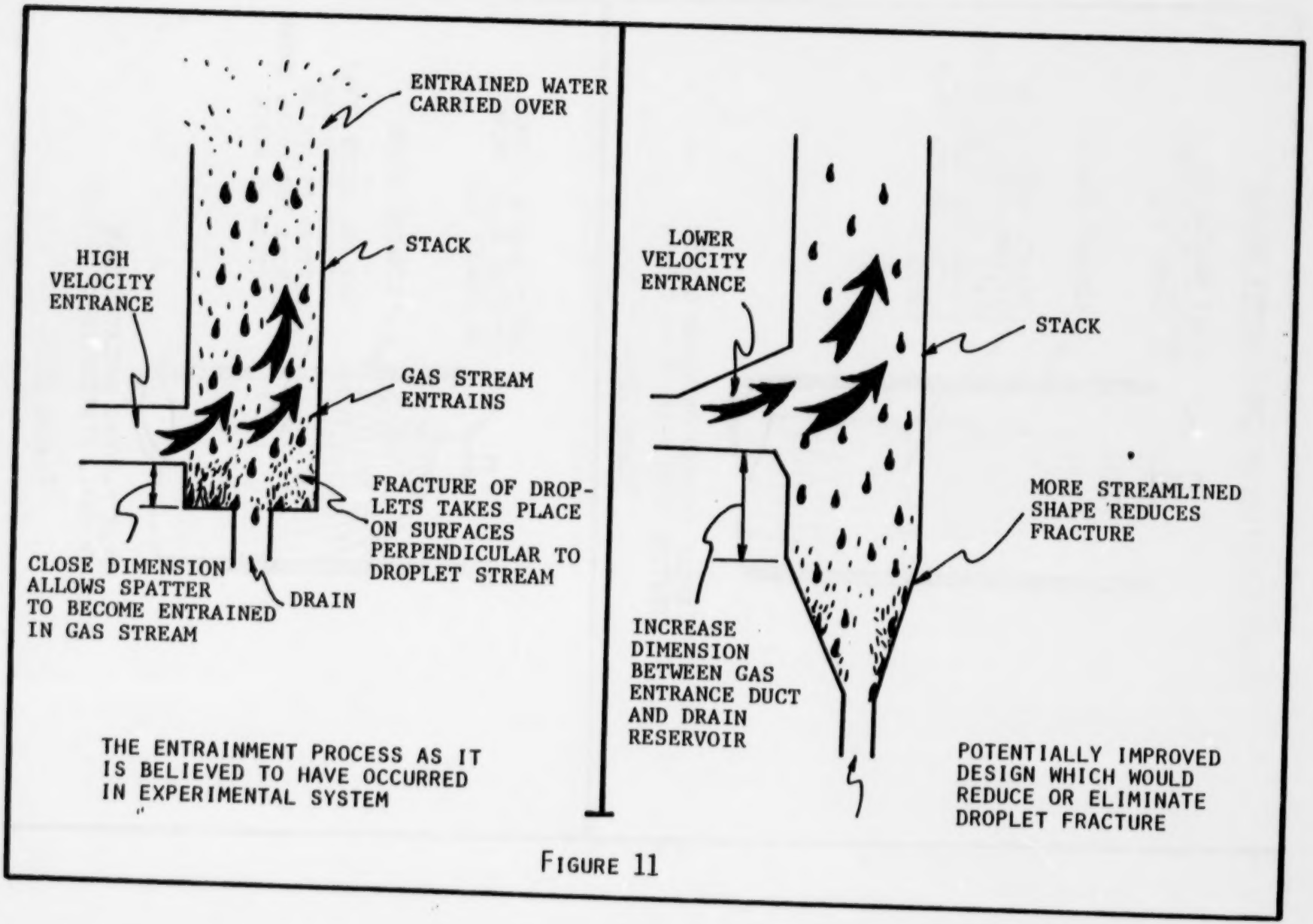

ENTRAINED WATER CARRIED OVER
STACK
HIGH VELOCITY ENTRANCE
GAS STREAM ENTRAINS
FRACTURE OF DROPLETS TAKES PLACE ON SURFACES PERPENDICULAR TO DROPLET STREAM
CLOSE DIMENSION ALLOWS SPATTER TO BECOME ENTRAINED IN GAS STREAM
DRAIN
THE ENTRAINMENT PROCESS AS IT IS BELIEVED TO HAVE OCCURRED IN EXPERIMENTAL SYSTEM
LOWER VELOCITY ENTRANCE
STACK
MORE STREAMLINED SHAPE REDUCES FRACTURE
INCREASE DIMENSION BETWEEN GAS ENTRANCE DUCT AND DRAIN RESERVOIR
POTENTIALLY IMPROVED DESIGN WHICH WOULD REDUCE OR ELIMINATE DROPLET FRACTURE

FIGURE 11

5.4.7 Flue Gas Temperatures:

The temperature of the hot flue gas entering the experimental stack varied in temperature during the testing from 312°F to 444°F. As seen in Appendix C the change in inlet gas temperature during any one series of tests was not this extreme; but, a continuous change in temperature was common and the influence this had on the test results is difficult to measure. In general, we can conclude that this problem tended to reduce the accuracy of quantitative systems analysis.

5.4.8 Cooling Water Temperature:

During the construction of the test facility it was agreed that the cooling water would be supplied from the domestic cold water service delivered to campus buildings. However, we found after installation that the water temperature was considerably increased during the treatment process. Inlet temperatures at the stack were found to be running generally about 75°F. While testing was possible at these water temperatures and data on heat exchange performance were recorded, we were anxious to experiment with a lower temperature cooling water.

During the last week of January the cooling water supply line was replumbed to connect with a raw water supply upstream of the treatment plant. Beginning February 2 all tests were run using the raw water to supply the cooling requirement. Typically the temperatures of this water at the inlet to the stack were 55°F. However, some variance was experienced during the tests as shown in Appendix C with temperatures reaching 66°F at times. It was never determined what was causing these variations.

5.4.9 Cooling Water Flow Rates:

Control of cooling water flow rate was easily accomplished using gate valves in the supply line. As shown in Appendix C flow rates from 0 to +40 GPM were routinely incrementally set during testing. Some problem was experienced in holding the flow rates constant during the test interval. This was caused by pressure fluctuation due to varying demands from other parts of the University system.

5.5 Termination of Tests:

By the end of the testing in January plans were made to correct several of the system control problems and extensive testing was planned for the latter part of February and first half of March. However, during the first week in February problem resulted in the termination of the experiment.

During the last week of January the power plant engineer became aware of an irregular vibration in the main induced draft fan of boiler #1. Referring to Figure 2 one can see that it was through the side of this induced draft fan housing that we gained access to the boiler stack with our system flue gas supply duct. Since the vibration continued, power plant personnel shut down boiler #1 during the second week of February to inspect the induced draft fan.

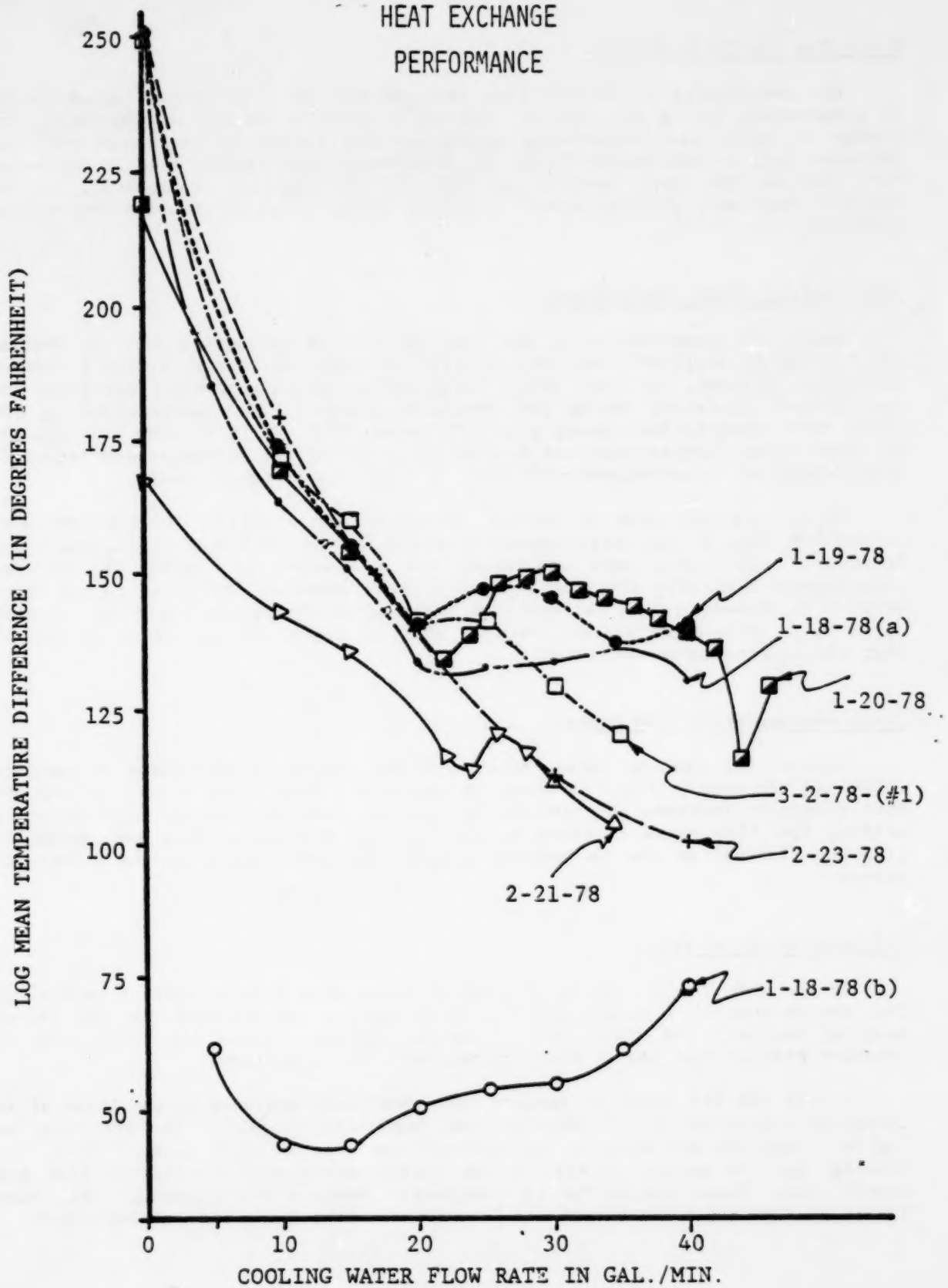

HEAT EXCHANGE
PERFORMANCE
LOG MEAN TEMPERATURE DIFFERENCE (IN DEGREES FAHRENHEIT)
250
225
200
175
150
125
100
75
50
0
10
20
30
40
COOLING WATER FLOW RATE IN GAL./MIN.
1-19-78
1-18-78(a)
1-20-78
3-2-78-(#1)
2-23-78
2-21-78
1-18-78(b)

FIGURE 12

They found that a buildup of fly ash and particulate on the fan blades was causing a rotational imbalance. After cleaning the blades, the boiler was refired and the vibration was gone. This was the first time the problem had occurred and there was no apparent determination of the cause. Since the experimental system was the only change to the original system, the added apparatus was suspected as the source of the problem.

It was decided that testing would continue, but since we could not allow the experiment to jeopardize the University's supply of heat and electric power, we continued with the understanding that if the problem reoccurred we would suspend testing until it could be corrected.

On February 21, testing resumed. Further modification of the system was limited to changes in the cooling water supply and the change of the orifice plate in the injection nozzle previously described. The intent was to obtain all data possible in a short time.

We requested sulfur oxide measuring equipment which had been offered by the U.S. Environmental Protection Agency, but it was out of service. We then prepared for particulate sampling and wastewater analysis.

On February 24 water and gas sampling began and continued for all tests following that date. No problems were encountered with water sampling; however, the particulate sampling equipment proved difficult to use and breakdowns and aborted tests were common.

On February 24 the vibration in the induced draft fan was again noticed and boiler #1 was scheduled for shutdown on March 3. At that time the experimental system would be disconnected indefinitely from the power plant stack. The testing continued through March 2. When the fan was inspected again the particulate buildup was observed and removed. After the experimental system was disconnected, the boiler was refired and the problem with the induced draft fan was never again observed.

PARAMETRIC DATA

TABLE 2

$T_{g,i}$	$T_{g,o}$	$T_{g,o}$*	$T_{w,i}$	$T_{w,o}$	$T_{w,o}$*	W_i	W_o*	PWR	M_w(GPH)	V_g	F.R.
419	245	272	57	107	95.0	.0626	.0428	31.5	10	10.5	1.55
430	221	266	58	100	97.0	.0626	.0413	34.1	15	12.5	1.75
444	205	232	57	93	93.5	.0626	.0350	44.0	20	12.0	2.40
436	190	204	55	85	89.9	.0626	.0307	50.9	25	13.0	2.80
432	171	200	56	85	90.2	.0626	.0305	51.3	30	14.0	2.85
431	166	123	55	79	81.6	.0626	.0182	70.9	35	10.5	4.90
434	188	224	58	91	93.7	.0626	.0345	44.8	20	11.7	2.45
434	211	266	60	101	98.2	.0626	.0415	33.7	15	11.9	1.80
431	236	336	59	108	101.0	.0262	.0513	18.0	10	14.0	.90
394	180	81	67	85	83.0	.0626	.0154	75.4	40	7.8	8.30
394	176	79	56	77	75.0	.0626	.0122	80.5	35	7.8	7.10
394	224	216	70	100	91.0	.0626	.0373	40.4	17	7.8	3.40
396	239	231	66	105	100.5	.0626	.0404	35.5	17	8.0	2.00

NOMENCLATURE

T - Temperature
W - Humidity Ratio
PWR - Percent Water Removed
M_w - Gallons per Minute Water
V_g - Velocity of Flue Gas
F.R.- Flow Ratio

Subscripts:
i - in
o - out
g - gas
w - water

Superscripts:
* - Predicted Values

6. ANALYSIS OF RESULTS

This section is divided into three major parts. First the experimental system is analyzed as a mechanical heat exchange apparatus and ice fog control device. The second section describes the analysis of the system as a particulate scrubber and finally the cooling water analysis and treatment is addressed.

6.1 Mechanics of the Heat Exchange Process:

The following analysis considers only a portion of the test data listed in Appendix C since it was not considered necessary to conduct an analysis for all tests. Recall from Figure 12 that the log mean temperature difference response of the system as a function of mass flow ratio was similar for the majority of tests conducted. We have selected for analysis inclusion of those tests from these test series for which particulate sampling and waste water analysis were also performed.

Data from several series of these tests conducted using the stack are presented in Table 2. The primed values in this table are the analytical results generated by the computer program presented in Appendix A. Because humidity ratio measurements were not obtained during the testing, the humidity ratio of the hot flue gas was assumed constant at the value reported by Dames and Moore (1973). Also the mean drop size was not measured. However an estimate of the drop diameter can be made using the relationship presented in Porteous and Wallis (1965)

$$d = \left(\frac{\sigma_w d_o g_c}{g \rho_w} \right)^{1/3} \tag{25}$$

where σ_w is the surface tension of the water, ρ_w is the density of water, and d_o is the diameter of the orifice. The holes in the spray head had a diameter of .109 inches which at 50°F would produce drops having a mean diameter of .173 inches.

The terminal velocity of the drops can be calculated by equating aerodynamic drag force to the net bouyant force or

$$V_d = \sqrt{\frac{4d_g (\rho_w - \rho_g)}{3C_d \rho_g}} \tag{26}$$

where V_d is the terminal velocity of the drops and C_d is the drop drag coefficient. Referring to Chen and Trezek (1977) two equations are presented for drag coefficient of drops as a function of Reynolds numbers

$$C_d = \frac{24}{Re} + \frac{6}{1+Re} + 0.27 \quad 1 \leq Re \leq 100 \tag{27}$$

and

$$C_d = .6649 - .2712 \times 10^{-3} Re + 1.220 \times 10^{-7} Re^2 - 10.919 \times 10^{-12} Re^3 \quad 1000 \leq Re \leq 3600 \tag{28}$$

At an average gas temperature of 250°F, the terminal velocity of the drops are 37 feet per second at a Reynolds number of 1910.

A comparison of calculated water temperature leaving the stack and actual water temperature leaving the stack is shown in Figure 13. Although agreement is not perfect, certainly the predicted results are close enough to the measured values to support the validity of the computer model. When the stack was operated at zero mass flow ratio (no water flow), a temperature difference ranging from 50°F to 100°F occurred between the bottom and top of the stack. This temperature difference is caused by the heat loss through the walls of the stack and is a function of gas flow rate, gas temperature and ambient outdoor temperature. To account for this heat loss, a temperature correction was applied to the measured temperatures at the top of the stack. These corrected temperatures are presented in the second column of Table 2. The gas temperatures leaving the stack as corrected are probably still in error as presented. This is due to the fact that many fine cold drops - either generated at the nozzle or by shattering at the bottom of the stack - were "carried over" by the hot flue gas, impinged on the thermocouple temperature sensors and caused a low temperature reading.

The columns in Table 2 that present the humidity ratio (W) of the flue gas entering and leaving the stack clearly indicate a decrease in the moisture content of the exhaust gas at the top of the stack. This decrease ranged from 18% to 80% which would certainly lead to a decrease in the visual vapor plume at the stack discharge; however, this was not seen since apparently there was sufficient mist carry-over and flashing to vapor fog to mask the dehumidifying effect of the counter flow spray.

6.2 Particulate Sampling:

6.2.1 General:

Particulate sampling is a standard method of determining the amount of suspended fly ash in the stack exhaust of coal-fired power plants. In this study sampling was done using a device especially designed for large stack sampling, the Emission Parameter Analyzer manufactured by the Western Precipitation Division of the Joy Manufacturing Co. (see description in Appendix B). Because of the fragile nature of glass impingers and the hazardous situation in which the analyzer was used, a condenser was substituted for the impinger train as described in operating instructions of the analyzer (Joy Manufacturing Co., undated). The condenser used was an automobile heater core heat exchanger, which was plumbed into the glass system of the analyzer using specially made glass fittings. This sampling train made it more difficult to do an accurate measurement of the water condensed from the gas flow for isokinetic determination, but did allow for safe handling and a series of tests to be made in one day.

Sampling was done at the top of the stack, and every effort was made to place the pitobe nozzle so that effects of the scrubber were minimized. Because of the cumbersome size and design of the EPA sampler, it was necessary to mount it on a makeshift platform on the access catwalk at the top of the stack structure. Figure 14 is a photo showing the isokinetic probe extending over the stack exit. The EPA sampler was originally designed to operate in a large stack along a suspension rail which would enable it to be moved with ease. This situation did not afford that ease of operation.

Given the sampling parameters of the experimental stack, the optimum nozzle diameter for the pitobe in this test situation is ½". Particulate sample filters were the standard fiberglass mat type used in high volume samplers, and designed

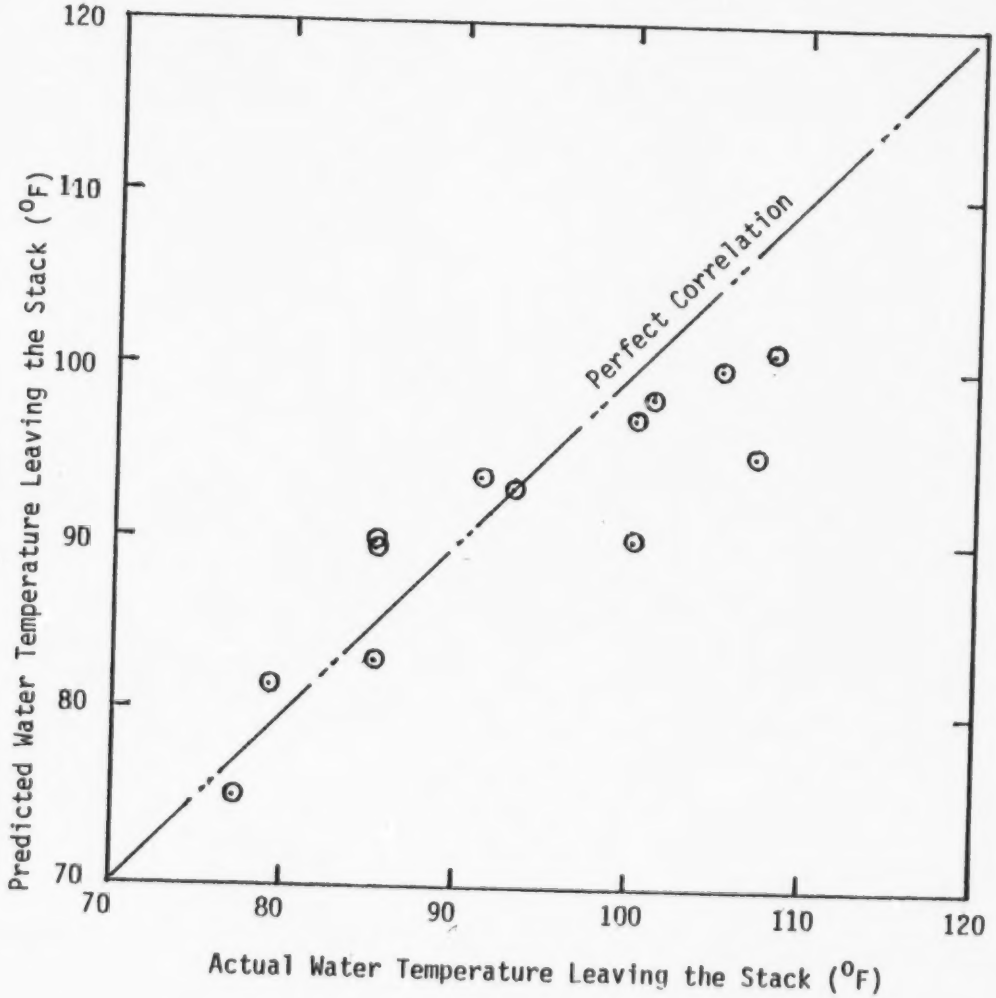
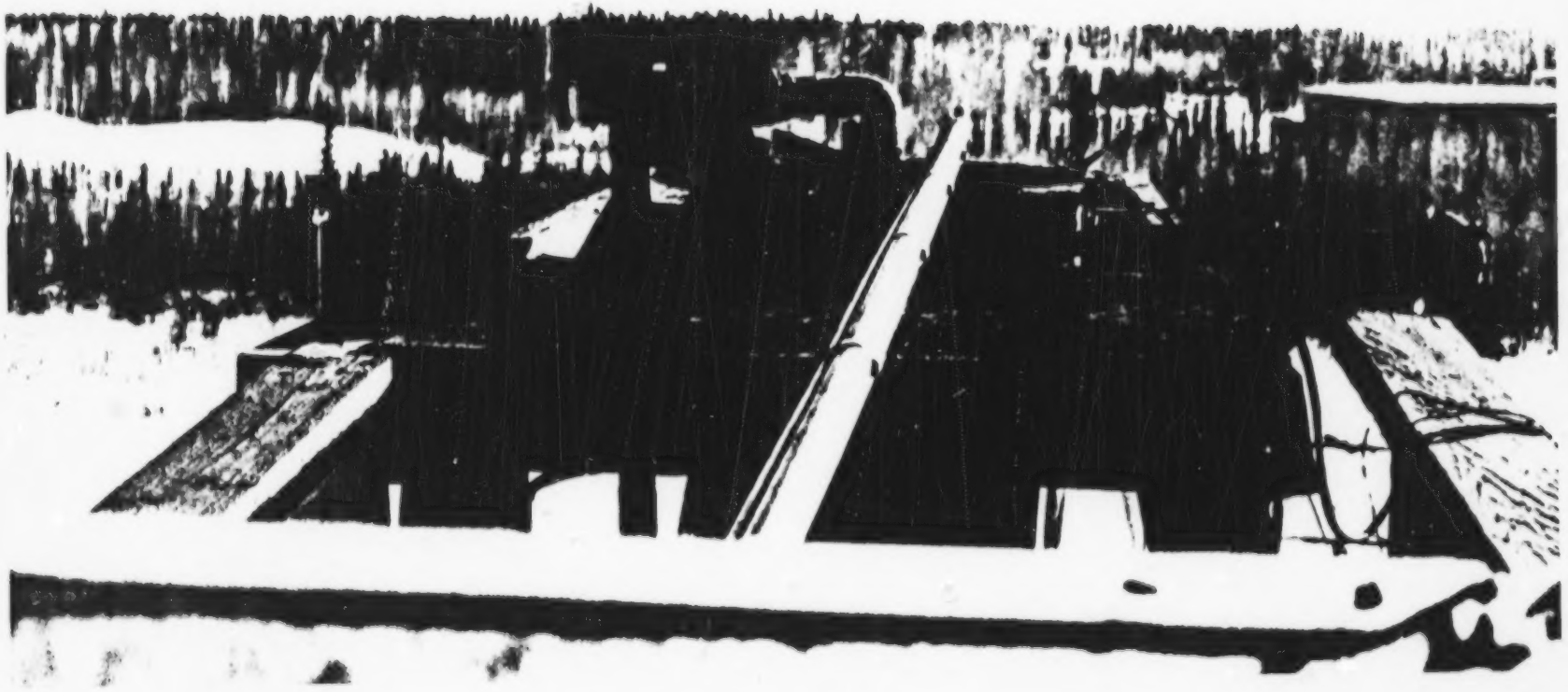

120
110
100
90
80
70
70
80
90
100
110
120
Predicted Water Temperature Leaving the Stack (°F)
Actual Water Temperature Leaving the Stack (°F)
Perfect Correlation

FIGURE 13

PARTICULATE SAMPLING WITH
ISOKINETIC PROBE AND THE
EMISSION PARAMETER ANALYZER
FIGURE 14



to trap virtually all particulates. These filters were cut to fit the filter holder and pre-massed on a precision Mettler balance accurate to 0.5 mg. Each massed filter was handled with tweezers and sealed in an envelope to avoid pre-contamination before use.

6.2.2 Procedure:

A description of the procedure for particulate tests is given in the Federal Register, Volume 36, Number 247, part number 2. This technique was followed except for the substitution of the condenser for the impinger train. In addition, the comparative results will be a relative comparison of the particulate load in the flue gas stream, since the particulate sampling pitobe was only cleaned at the end of each day. Sampling was done on two days; 13 particulate samples were collected. After each run the particulate filter was placed in a plastic "whirl-pak" bag to avoid further contamination. After each day of runs the sampling system was flushed several times with acetone and the washings were placed in a tared evaporating dish and evaporated to dryness and weighed. Each of the particulate filters was placed on a drying rack and dried in a soil sample oven at 100°C for consecutive 24 hour periods until the mass difference was less than 0.5 mg. This process required a minimum of 72 hours of drying.

Calculations were done using the relationships described in the operating instructions for the analyzer. Due to the use of the condenser, stack temperature measurements and filter holder measurements were not made using the Emission Parameter Analyzer. Instead, thermocouple stack temperatures were used in place of those measurements. The calculations follow. In the labeling of the calculations the following code was used: the series labeled 1A, 2A, 3A, and 4A was collected on February 24, 1978; the series labeled 3, 4, 5, 6, 7, 8, 9, 10, 11 was collected on March 2, 1978.

6.2.3 Calculations to determine air quality sampling standard values and concentrations:

$$VM(std) = VM \frac{P(bar) + \frac{H}{13.6}}{P(std)} = \frac{.0334}{\text{in Hg.}} VM \left[P(bar) + \frac{H}{13.6}\right] \qquad (29)$$

where:

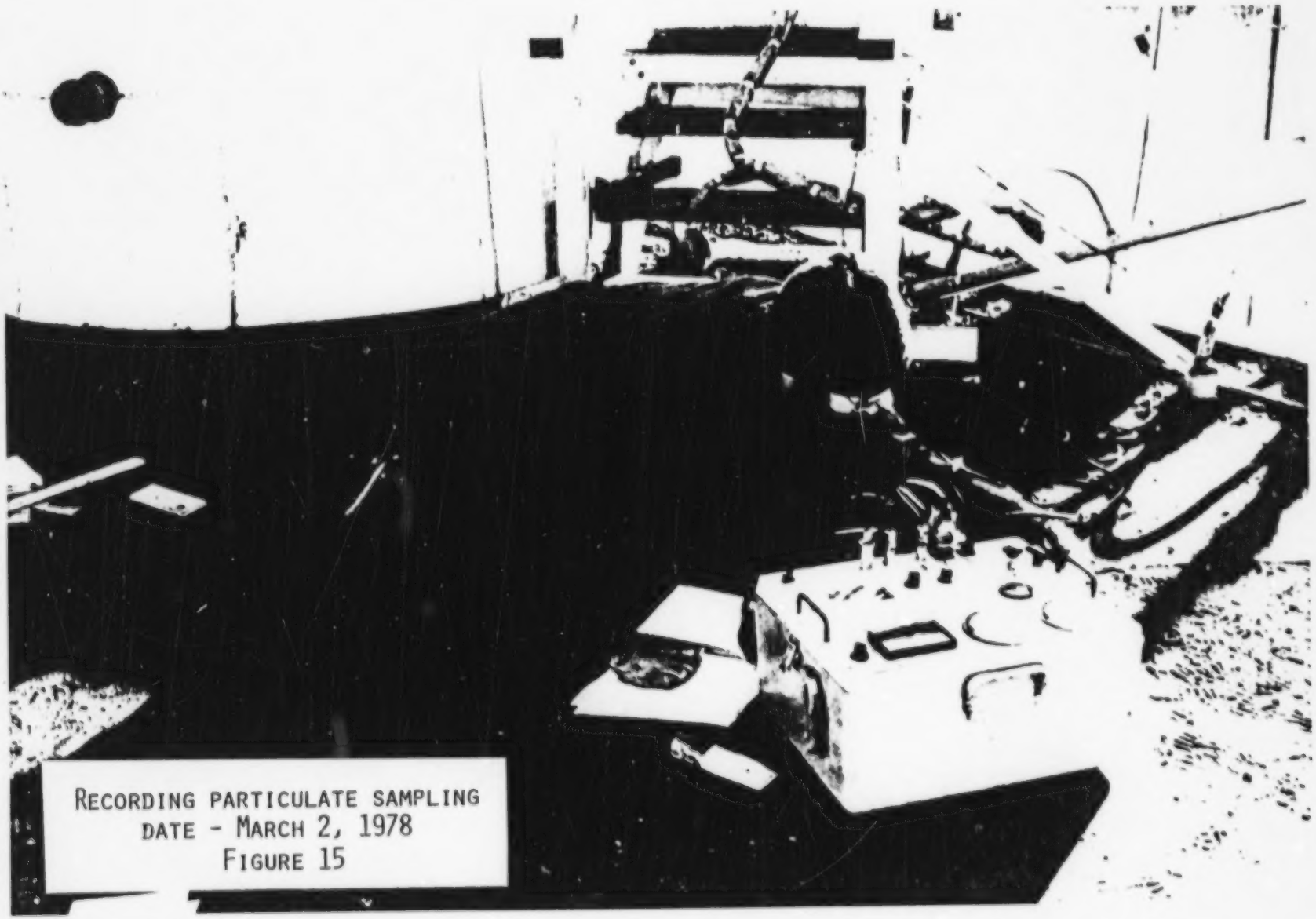
VM(std) = volume of gas sample through the meter at standard conditions, cu. ft.

VM = measured volume of the gas sample

P(bar) = barometric pressure at the orifice

$\frac{H}{13.6}$ = $\frac{\text{average pressure drop across the orifice}}{\text{specific gravity of mercury}}$

P(std) = absolute pressure at standard conditions, 29.92 in Hg.



RECORDING PARTICULATE SAMPLING
DATE - MARCH 2, 1978
FIGURE 15

TEST 1A, FEBRUARY 24, 1978

$$VM(std),\ 1A = \frac{.0334}{\text{in Hg.}}\ 15.4 \text{ cu. ft.}\quad 29.78 + \frac{1.7}{15.6}$$

$$VM(std),\ 1A = 15.38 \text{ cu. ft.}$$

$$VM(std),\ 2A = \frac{.0334}{\text{in Hg.}}\ 15 \text{ cu. ft.}\quad 29.78 + \frac{1.7}{13.6}$$

$$VM(std),\ 2A = 14.98 \text{ cu. ft.}$$

$$VM(std),\ 3A = \frac{.0334}{\text{in Hg.}}\ 15 \text{ cu. ft.}\quad 29.78 + \frac{1.7}{13.6}$$

$$VM(std),\ 3A = 14.98 \text{ cu. ft.}$$

$$VM(std),\ 4A = \frac{.0334}{\text{in Hg.}}\ 15 \text{ cu. ft.}\quad 29.78 + \frac{1.78}{13.6}$$

$$VM(std),\ 4A = 14.99 \text{ cu. ft.}$$

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$$VM(std),\ 3 = \frac{.0334}{\text{in Hg.}}\ 15 \text{ cu. ft.}\quad 30.17 \text{ in.} + \frac{2.31}{13.76}$$

$$VM(std),\ 3 = 15.19 \text{ cu. ft.}$$

After same calculations....

VM(std), 4 = 15.20 cu. ft.
VM(std), 5 = 15.21 cu. ft.
VM(std), 6 = 15.20 cu. ft.
VM(std), 7 = 15.20 cu. ft.
VM(std), 8 = 15.20 cu. ft.
VM(std), 9 = 15.16 cu. ft.
VM(std), 10 = 10.15 cu. ft.
VM(std), 11 = 10.15 cu. ft.

Next, it is necessary to calculate the concentration of particulates in the flue gas samples in pounds per cubic foot.

$$CS = \frac{\frac{1}{453{,}600}\ \frac{\text{lb.}}{\text{mg.}}\ Mm}{VM(std)} = 2.205 \times 10^{-6}\ \frac{Mm}{VM(std)} \qquad (30)$$

where:

CS = concentration of particulate matter in stack gas, lb./scf

Mm_i = total amount of particulate collected in the i^{th} test

VM(std) = measured volume of gas sample at standard conditions, cu. ft.

FEBRUARY 24, 1978 TESTS

CS 1A = 7.168×10^{-6} lbs./scf
CS 2A = 9.567×10^{-6} lbs./scf
CS 3A = 3.679×10^{-6} lbs./scf
CS 4A = 2.205×10^{-6} lbs./scf

MARCH 2, 1978 TESTS

CS 3 = 1.142×10^{-5} lbs./scf
CS 4 = 6.049×10^{-6} lbs./scf
CS 5 = 2.205×10^{-6} lbs./scf
CS 6 = 1.084×10^{-5} lbs./scf
CS 7 = 1.146×10^{-5} lbs./scf
CS 8 = 1.018×10^{-5} lbs./scf
CS 9 = 7.316×10^{-6} lbs./scf
CS 10 = 3.714×10^{-6} lbs./scf
CS 11 = 1.651×10^{-6} lbs./scf

Calculations of isokinetic variation:

$$I = \frac{\frac{V1C\ pH2O\ R}{mH2O} + \frac{VM}{TM}\ P(bar) + \frac{H}{13.6}}{O\ VS\ PS\ AN} \qquad (31)$$

$$= \frac{1.667\ \frac{min.}{sec.} \quad 0.00267\ \frac{in\ Hg\text{-}cu.ft.}{ml\text{-}^{o}R}\ V1C + \frac{VM}{TM}\ P(bar) + \frac{H}{13.6}\ TS}{O\ VS\ PS\ AN}$$

where:

I = percent of isokinetic sampling

V1C = total volume of liquid collected in impingers and silica gel, ml.

pH2O = density of water, 1 g./ml.

R = ideal gas constant, 21.83 inches Hg-cu.ft./lb. mole-^{o}R.

mH2O = molecular weight of water, 18 lb./lb.-mole.

VM = volume of gas sample through the dry gas meter (meter conditions), cu. ft.

TM = absolute average dry gas meter temperature, ^{o}R.

P(bar) = barometric pressure at sampling site, inches Hg.

H = average pressure drop across the orifice, inches H2O

TS = absolute average stack gas temperature ^{o}R.

O = total sampling time, min.

VS = stack gas velocity, ft./sec.

PS = absolute stack gas pressure, inches Hg.

AN = cross-sectional area of nozzle, sq. ft.

FEBRUARY 24, 1978 TEST SERIES

$$I = \frac{1.667\ \frac{\text{min.}}{\text{sec.}}\quad 0.00267\ \frac{\text{in Hg-cu.ft.}}{\text{ml}\ ^{\circ}\text{R}}\quad \text{V1C} + \frac{\text{VM}}{\text{TM}}\quad \text{P(bar)} + \frac{\text{H}}{13.6}}{\text{O VS PS AN}}\quad \text{TS}$$

$$= \frac{1.667\quad 0.00267\ 2.5 + \frac{15\ \text{cu.ft.}}{499.69}\quad 29.89 + \frac{2.35}{13.6}\quad 729^{\circ}\text{R}}{(.00272\ \text{ft.}^2)\ (15\ \text{min.})\ (20\ \text{ft./sec.})\ [(.0735)(.6)+13.6]}$$

$$= \frac{1.667\ [6.67\text{x}10^{-3} + 9.024\text{x}10^{-1}]\ 729^{\circ}\text{R}}{11.11}$$

$$= 99.43$$

So, isokinetic sampling percentage lies within the prescribed range of 90 which is equal to or less than "I" which is equal to or less than 110, for these tests.

MARCH 2, 1978 TEST SERIES

$$I = \frac{1.667\quad (0.00267)\ 2.5\text{ml} + \frac{15\ \text{cu.ft.}}{499.69}\quad 30.17 + \frac{2.50}{13.6}\quad 749^{\circ}\text{R}}{(.00272\ \text{ft.}^2)\ (15\ \text{min.})\ (20\ \text{ft./sec.})\ (.0735)\ (.6) + 13.6}$$

$$= \frac{1.667\ [6.675\text{x}10^{-3} + 9.11\text{x}10^{-2}]\ 749^{\circ}\text{R}}{11.11}$$

I = 103.15, which is isokinetic also.

With the assumed estimates of water content and average stack temperature, the tests fall within the range of isokinetic sampling. Results of these tests were not intended to test scrubbing of particulates per se, but our interest was in providing correlations and mass balance comparisons to determine the expected particulate and pollutant load removed from the gas by the scrubbing water. This enables evaluation of the need for additional water treatment of the scrubber water, which may add costs and inefficiencies to the system.

6.2.4 Mass Balance Comparison:

As a check on the efficiency of scrubbing and consistency of our results in both water sampling and particulate sampling, parallel calculations were done to determine if the total amount of solids in the flue gas stream was comparable in each test. These comparisons will have some scatter, since it is unlikely that the particulate load is consistent over time, due to variability in coal quality and other combustion factors.

The amount of particulates scrubbed out of the flue gas depended upon many factors including the spray pattern, flow ratio (defined as the ratio of the weight of the cooling medium per unit time to the weight of the hot flue gas per unit time), the water temperature and flue gas temperature.

In this case, the study involved concentration comparisons based on the flow ratio of each test. Also, different mass flow rates were involved since some of the tests were done with the flow dampers in the test system closed.

The mass of particulates in the flue gas stream leaving the top of the stack in a 15-minute sampling period is given by:

$$CS\ R\ (15\ min.)\ 60\ \frac{sec.}{min.} = PM \qquad (32)$$

where:

CS = the particulate concentration
R = the volumetric flow rate of the flue gas
PM = the total mass of the particulates emitted during the 15-minute test

In a similar manner, the particulates contained in the scrubber water can be calculated using this relation:

$$\frac{(I\text{-}nsf)\ (FW)\ (15\ min.)\ (6.243 \times 10^{-5})\ lbs./cu.ft.}{7.48\ gal./cu.\ ft.\quad mg/l} = PMW \qquad (33)$$

where:

I-nsf = the increment over the background level of total non-filterable solids in the scrubber water in mg/l
FW = the volumetric flow rate of scrubber water in gals./min.
PMW = the weight of particulates in the scrubber water

Table 3 lists parameters of tests done on March 2. Some of the tests were made without collecting water samples, so the comparisons could not be made. However, for tests 3, 4, 7, 8, and 11, comparisons are possible for both the increment of non-filterable solids in the scrubber water over the background to the particulates in the flue gas, and the increment of total solids in the scrubber water compared to the particulates in the flue gas as shown in Table 4. Table 5 shows the total solids increment over the raw scrubber water for the five tests of interest.

Figure 16 is a plot of the particulate load in the fly ash compared to both the non-filterable solids load and the total solids load in the scrubber water. The filters used for both filtration tests (flue gas and non-filterable solids), were of the same material to eliminate any discrepancy in efficiency. Figure 16 shows the effects of different parameter variation on the particulate distribution. As might be expected, scrubber efficiency in removing particulates from the flue gas increases with the mass flow ratio. This is shown clearly in the difference between tests 3 and 4. The flow ratio was more than doubled in test 4, and the total particulate load increased by 52%. At the same time the total mass of particulates in the flue gas above the scrubber as measured by the EPA apparatus dropped by approximately 50%.

In the later tests, flow ratios of 1.7 and 1.0 were shown to be inefficient in removing particulates from the flue gas stream. For a flow ratio of 1.7 as in test 7, the total particulates in the flue gas were almost twice the weight of those in the scrubber water, and non-filterable solids were a small fraction (less than 5%) of total particulates scrubbed from the flue gas. This may indicate a decline in scrubbing of larger (non-filterable) particulates as a function of the flow ratio of the scrubber water.

TEST CONDITIONS AND RESULTS

MARCH 2, 1978

TABLE 3

TEST NUMBER	CONCENTRATION OF PARTICULATES IN FLUE GAS µg/l	CONCENTRATION OF NF SOLIDS IN SCRUBBERWATER µg/l	MASS FLOW RATIO kg water / kg flue gas	VELOCITY HEAD IN hg.	SCRUBBER FLOW RATE
#3	.1829	26.3	2.8	.35	25
#4	.0969	28.0	5.9	.13	30
#5	.0353	-	4.8	.25	35
#6	.1736	-	-	.25	20
#7	.1836	6.0	1.7	.27	15
#8	.1631	15.0	1.0	.43	10
#9	.1172	-	no scrubbing	.45	-
#10	.0595	-	-	(-).04	-
#11	.0264	25.0	~3.0	(-).04	10

TOTAL MASS COMPARISON

TABLE 4

TEST NUMBER	PARTICULATE CONCENTRATION lbs/SCF	VOLUMETRIC FLOW RATE ft^3/sec	TOTAL PARTICULATE MASS
#3	1.142×10^{-5}	21.2	.218 lbs
#4	6.049×10^{-6}	14.2	.077 lbs
#5	2.205×10^{-6}	19.4	.038 lbs
#7	1.146×10^{-5}	19.4	.200 lbs
#8	1.018×10^{-5}	26.5	.242 lbs
#11	1.651×10^{-6}	5.3	.078 lbs

TEST NUMBER	NONFILTERABLE SOLIDS INCREMENT OVER BACKGROUND		VOLUMETRIC FLOW RATE OF SCRUBBERWATER	NONFILTERABLE SOLIDS LOAD
	mg/l	lb/ft^3		
#3	26.3	1.64×10^{-3}	25 gpm	.0823 lbs
#4	28.0	1.75×10^{-3}	30 gpm	.1052 lbs
#5	-	-	35 gpm	-
#7	6.0	0.37×10^{-3}	15 gpm	.0112 lbs
#8	15.0	0.94×10^{-3}	10 gpm	.0188 lbs
#11	25.0	1.56×10^{-3}	10 gpm	.0312 lbs

MASS COMPARISON

-TOTAL INCREMENT OVER RAW WATER-

TABLE 5

TEST NUMBER	TOTAL SOLIDS INCREMENT	VOLUMETRIC FLOW RATE OF SCRUBBERWATER	TOTAL WEIGHT OF SOLIDS
#3	35 mg/l	25	.1095 lbs
#4	74 mg/l	30	.2779 lbs
#7	58 mg/l	15	.1089 lbs
#8	51 mg/l	10	.0638 lbs
#11	28 mg/l	10	.0350 lbs

COMPARISON OF FLY ASH AND PARTICULATE LOADS IN FLUE GAS AND COOLING WATER EFFLUENT

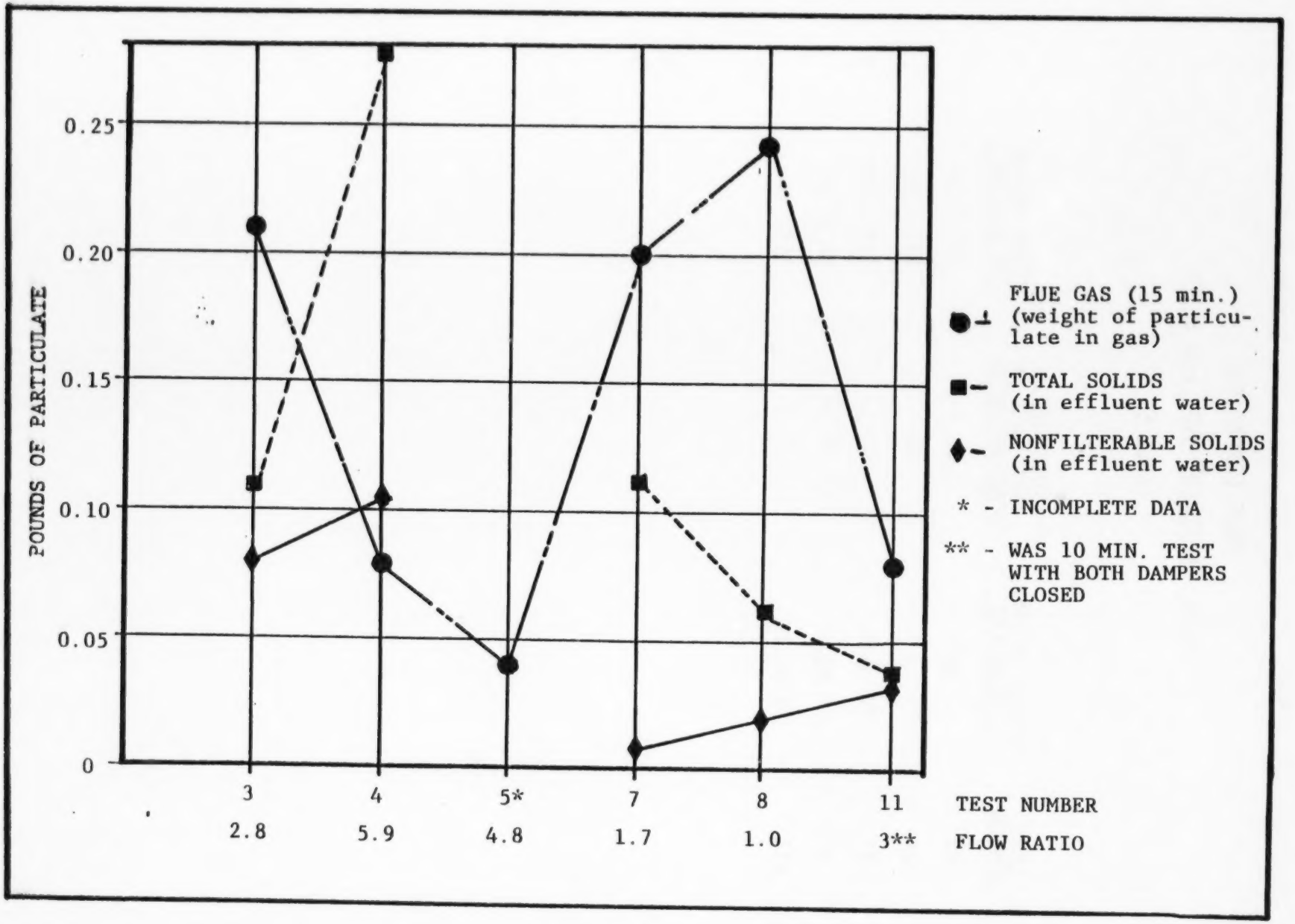

FIGURE 16

The data showed generally expected correlations of flow ratio and scrubbing efficiency in congruence with our previously calculated flow ratios necessary for dehumidification of the flue gases. This was encouraging, but due to the early termination of the experiment we were unable to further the complementary nature of dehumidification scrubbing and particulate scrubbing.

Results of tests based on the particulate sampling indicate that in no case did the particulate load in the flue gas stream exceed the statutory limit of 0.10 grains/scf (1.4786×10^{-5} lbs./scf). Dames and Moore (1973) tested the University power plant emissions and found that boiler #1, the same boiler from which flue gas was obtained in this study, had an average particulate emissions rate of 0.089 grains/scf (1.3159×10^{-5} lbs./scf). This is consistent with the range of measured values obtained in this work (1.651×10^{-6} to 1.146×10^{-5} lbs./scf).

6.2.5 Conclusions from air quality studies:

Although the data gathered from this work are insufficient to establish conclusions, the results tend to affirm that countercurrent scrubbing provides the dual benefits of scrubbing particulates from the flue gas as well as dehumidification.

6.3 Wastewater Disposal:

6.3.1 Data:

The scrubbing water effluent was weakly acidic and had a blackish tinge. It had a hardness of around 300 mg/l (as $CaCO_3$) which is within the range of hardnesses normally encountered for the untreated well water used as the source of scrubbing water. A chemical analysis of two of the scrubbing waters and the source (background) water appears in Table 6. Here the wastewater is characterized by both the flowrate (10 to 35 gpm) and the label "S" is used to denote supernatant after settling. Note that the concentrations of many of the dissolved inorganics were not appreciably different in the wastewater from the feedwater. From the limited data available, it appears that only boron, copper and zinc increased appreciably in concentration as a result of the scrubbing process. It is believed that the very high iron concentration shown in Table 6 is a result of an inhomogeneity in the sample since the data in Table 6 indicate only small changes in iron concentration.

The data in Table 6 were obtained using an outside firm. Testing indicated the scrubbing water generally had only slightly higher value for a given parameter than the background water. The limited data in the last two columns show that the levels of dissolved materials, obviously were not reduced by settling.

The data appearing in Tables 7 and 8 were obtained at the University of Alaska. Unless otherwise noted, the non-filterable solids were collected using the same kind of filter paper used for the stack gas sampling. For each sample appearing in Table 8, the three data points were obtained independently, i.e. column 3 was not obtained by subtracting column 2 from column 1. Hence, the accuracy of the results can be gauged by seeing the difference between the total

SCRUBBING WATER ANALYSIS

TABLE 6

Samples Received: March 9, 1978
Samples Acquired By: Institute of Water Resources
University of Alaska
Dr. Ron Johnson

Parameter	2,15	Background	1,30,A	1,30,A,S
Alkalinity, mg/l as $CaCO_3$	251	294	-	-
Acidity, mg/l as $CaCO_3$	*	*	-	-
COD, mg/l	24	20	-	-
Nitrate, mg/l NO_3-N	0.61	0.57	-	-
Sulfate, mg/l SO_4	65	51	70	73
Sulfite, mg/l SO_3	<1	<1	-	-
Barium, mg/l	0.50	0.49	0.58	0.45
Beryllium, mg/l	<0.02	<0.02	-	-
Boron, mg/l	1.1	0.7	-	-
Cadmium, mg/l	<0.005	<0.005	-	-
Calcium, mg/l	90.2	92.6	89.4	89.8
Chromium, mg/l (total)	0.003	0.001	-	-
Copper, mg/l	0.166	0.029	-	-
Iron, mg/l	5150	10.8	19.7	1.88
Lead, mg/l	<0.05	<0.05	-	-
Magnesium, mg/l	27.1	27.0	-	-
Manganese, mg/l	0.068	0.062	-	-
Nickel, mg/l	<0.02	<0.02	-	-
Silica, mg/l	8.25	7.60	-	-
Strontium, mg/l	0.38	0.36	0.39	0.39
Zinc, mg/l	0.043	0.016	-	-

* Not enough sample to determine acidity.

SCRUBBING WATER ANALYSIS

TABLE 7

PARAMETER	1,10	1,10,S	2,10	1,35	Background,2	1,15	0,17
Conductivity ($\frac{\mu mhos}{cm}$)	590	590	600	550	600	-	-
Hardness, as $CaCO_3$	-	280	350	300	250	-	-
Iron (total)	16.7	.9	11.8	11	11.5	-	1.3
Manganese	<.1	<.1	2.2	.1	1.1	-	.8
Nitrate (NO_3-N)	1.3	.7	1.3	2.3	-	-	1.3
Sulfate	100	150	90	69	-	-	-
Turbidity (FTV)	190	7	155	105	120	-	180
pH	6	-	6	6	-	-	-
Alkalinity, as $CaCO_3$	-	-	-	-	-	170	-
Phosphate	-	-	-	-	-	1.9	-

PARAMETER	0,17,S	0,17,S,F	1,20	1,20,S
Conductivity ($\frac{\mu mhos}{cm}$)	630	630	-	-
Turbidity (FTV)	18	7	-	-
Color	-	-	100	20

NOTE: All concentrations in mg/l unless denoted otherwise.

SOLIDS LEVELS IN SCRUBBING WASTEWATER

TABLE 8

Sample	Total Solids	Nonfilterable Solids	Filterable Solids
Background 1	442	32	413
Background 2	420	24	400
Background 3	446	27	415
0,17 1	668	74	549
0,17 2	618	92 (.45μ filter)	534
0,17,S	533		
1,10	626		
1,10,S	500	6 (by subtraction)	
1,15	516	28	500
1,25	476	26	462
1,30	515	26	513
1,35	493	15	469
2,10	667		
2,15	470	25	428

NOTES: All concentrations in mg/l.
Nonfilterable solids defined as those retained by same filter paper used for air sampling unless otherwise noted.
All data obtained by direct weighing unless otherwise noted.

solids (TS) and the sum of the filterable and non-filterable solids (N-FS). Background water samples were taken on three different days including the day of the bulk of the tests. The variability here in the N-FS is significant in that the difference in this quantity between the sample and background water reflects the N-FS removed by the scrubbing water. Even though this number should not be negative, the fact that it sometimes is indicates the difficulty in using a scrubbing water analysis to infer particulate removals from the stack gas. It should be mentioned that each number quote usually reflects the weighing of three separate samples each to an accuracy of better than 2%. The differences among these three masses were typically less than 10% for the TS and 20% for the N-FS.

Other chemical quality data and physical quality data appear in Tables 7 and 8. The most significant results shown in these tables are: (1) the large reduction in iron concentration and (2) the large reduction in suspended (non-filterable) solids and turbidity achievable by settling. The latter was obvious by simply looking at the samples before and after settling occurred. A very fine black precipitate could be observed at the bottom of the containers after several hours. Similar results were observed by filtering the sample through a .45u glass fiber filter. Hence, there is a distinct possibility of improving effluent quality by gravity settling alone prior to discharge. This method of treatment is commonly used to treat flue gas scrubbing fluids (Nemorow 1971; U.S. EPA 1974; and Crowe 1976).

6.3.2 Wastewater Treatment:

One common method for separating fly ash from the scrubbing water is to use a decanting basin. Besides the data obtained here illustrating the large reductions in turbidity, color, iron, and non-filterable solids achievable by settling, similar results have been found by others for fly ash slurries (U.S. EPA 1974). Such slurries have much higher levels of suspended solids than the scrubbing water collected in this study. This is because of the large dilution available in the counter current spray process.

The wastewater flow of less than 40 gpm during the testing period was blended with the rest of the physical plant waste water. As of April 1978, this was being treated at College Utilities which uses an oxidation ditch. If this concept were applied to the entire stack flow, the wastewater flow of 910 gpm (1.3 mgd) would fall well within the hydraulic capacity of the Fairbanks Sewage Treatment Plant. This plant currently processes an average of 4 mgd of largely domestic wastewater. By 1980, the wastewater currently treated at College Utilities will be processed at the Fairbanks plant. A forced main with a capacity of over 4 mgd will be used to transport the wastewater to the municipal plant. The operating costs for this main increase with flow rate. Assuming no toxicity problems are posed by the metals in the wastewater, there is no technological reason why it couldn't be processed by the Fairbanks plant. If permission to do so were granted by the City of Fairbanks, there would be a user's fee (O'Neil 1978). But, this may not be desirable since the COD (see Table 6) of the wastewater is only around 20 mg/l. Assuming the BOD/COD ratio is less than one, it may not be cost effective to process this flow through a secondary treatment plant whose current effluent has a BOD around 30 mg/l (Johnson 1978).

Based on the data found in Tables 6 and 7, one would conclude that the metals in the scrubbing wastewater would not pose a toxicity threat to the microorganisms in a biological treatment plant. In fact, most of the metals common to those in these two tables and those analyzed for Fairbanks municipal wastewater are less concentrated in the scrubbing wastewater. Since there is no current toxicity problem with the raw sewage in Fairbanks, it is unlikely the addition of the scrubbing effluent would pose a toxicity problem. But, laboratory tests must be performed to confirm this before any decision is made to utilize the municipal plant.

There should be no problems associated with the increased thermal load on the plant. Currently the influent temperature averages around 60°F. The additional 1.3 MGD at less than 100°F (by the time it reaches the plant) will result in an average influent temperature of less than 73°F. This is in a very acceptable range with respect to biological treatment. In fact, if the scrubbing wastewater is first processed through a settling pond, its temperature at the point of entry into the Fairbanks plant may be less than 60°F.

6.3.3 Impact on Receiving Waters:

If the wastewater were to be discharged directly into the Chena or Tanana even with pre-settling, a discharge permit would have to be obtained from the Alaska Department of Environmental Conservation. This permit would only be granted if such discharges did not violate the Alaska water quality standards. With the proposed revisions (State of Alaska, 1978), there are standards on dissolved oxygen, temperature, pH, turbidity, fecal coliforms, dissolved inorganics, sediment, color, hydrocarbons, radioactivity, and total residual chlorine. Even though changes will probably be made, these proposed revisions will be used as a guideline. With the Chena River classified as Class B/C in the Fairbanks area, the river temperature due to the waste discharge can not rise more than 3.0°F above ambient. If the entire wastewater flow of 1.3 MGD assumed to be at 100°F is mixed with a minimum river flow of about 300 cfs (U.S. Dept. of Interior, 1973), the maximum temperature rise after mixing will be only .44°F. Here the river temperature before mixing is taken to be 34°F. During the non-winter months with the larger river flow rate and warmer temperatures, the temperature rise will be insignificant. Moreover, the wastewater temperature will most likely be less than 100°F. This will certainly be true if settling precedes discharge. Hence, there is no problem with respect to gross temperature rises in the Chena. However, the water quality standards on temperature refer to maximum temperature increases at the edge of a mixing zone. By using data presented in Carlson and Tilsworth (1977), one can conclude that the effluent will be rapidly mixed with the Chena River. For the Municipal Utilities System (MUS) cooling water flow of 29 MGD at a temperature of 10°C, a mixed zone temperature of 1°C was achieved within a few feet of the submerged discharge pipe. The upstream river temperature at the time of collection of this data was .1°C. Since the thermal load imposed by the scrubbing wastewater is ony about one-seventh of that of MUS, there should be no thermal pollution problem resulting from direct discharge into the Chena River.

One could make similar calculations to deduce the changes in other water quality parameters for either the Chena or Tanana Rivers. Since the flow rate of the latter is at least ten times that of the former, the dilutional effect will be much greater for the Tanana. Moreover, the Tanana has much higher solids and

turbidity levels. Hence, it should be generally true if water quality standards are not violated by discharging into the Chena, discharge into the Tanana should be allowed. Because of its physical proximity, discharge into the Chena would be much cheaper than discharge into the Tanana; but, such discharge can only be allowed if shown to be ecologically sound.

One could perform analogous calculations to those just done for the thermal discharge for turbidity, dissolved solids, and other water quality constituents. Because of the large dilution ratio available (around 150), one would find that the increment in most, if not all, of these parameters after mixing would not violate Alaskan water quality standards. For instance, the standards limit the increase in total dissolved solids (TDS) to less than one-third the natural concentration in the receiving water for Class C waters. Since the TDS level in the scrubbing water satisfies this after mixing with the Chena River, there is obviously no problem here. The maximum allowable turbidity increase is at least 10 NTU above natural conditions. Even if the turbidity of the Chena River were zero, there would probably be no violation here even if the settleable solids were not first removed in a sedimentation basin. With sedimentation preceding discharge, results of the scrubbing water analysis (Table 7) indicate no problem. The same can be said for iron after settling. After the supernatant is diluted by a factor of 150, the iron concentration would even meet suggested standards for surface drinking water supplies (U.S. EPA, 1973).

Detailed bioassay studies would have to be performed assessing the impact of all the trace metals, dissolved gases, organic compounds, and particulates on aquatic life before discharge to a receiving body would be allowed. Preliminary calculations indicate that there likely are no problems, especially if discharge is preceded by settling. For instance, the concentration of copper after dilution will be around 10 g/l using the data on Table 6. Levels up to 33 g/l are believed safe for hard waters and up to 6 g/l for soft waters (U.S. EPA, 1973). With hardness levels between 50 and 150 g/l as $CaCO_3$ (U.S. Dept. of Interior, 1973) the Chena is borderline between hard and soft (Sawyer and McCarty, 1978). Hence, the 10 g/l copper concentration may be allowable. The maximum acceptable concentrations of lead in waters classified to preserve aquatic life is 30 g/l (U.S. EPA, 1973). The concentration of lead after dilution would be less than .5 g/l. Similar comments can be made about the other trace metals appearing on Table 6.

The slight acidity of the wastewater should pose no problems for surface discharge given the buffering capacity of the Chena River and the dilution factor available. The nitrate, phosphate, sulfate, and sulfite ions are not mentioned by U.S. EPA (1973) as being parameters of concern for Alaskan Class B/C waters. Any synergistic effects resulting from the presence of these or any other ions will be determined by performing bioassay tests. The tremendous dilution ratio should make any dissolved oxygen changes in the Chena negligible because of possibly low dissolved oxygen levels in the wastewater. However, it may be necessary to aerate before discharge to satisfy state regulations.

7. CONCLUSIONS

The main purpose of this experimental project was to determine whether or not the counter-current scrubbing technique could be successfully demonstrated as an ice fog control technique for coal-fired power plants. The results of the project were inconclusive. However, the following conclusions should prove helpful in future attempts to develop a similar system.

7.1 Entrainment:

The problem of entraining fractured water droplets in the exhaust gas stream appears to be the single most important factor which will impede effectiveness of the system as an ice fog control technique.

7.2 Water Removal:

Removal of significant amounts of combustion-produced water vapor appears feasible from a real flue gas although we were unable to obtain a statistically defensible correlation between water removed and the mass of cooling water required.

7.3 Particulate Scrubbing:

The results of this experiment suggest that the counter-current spray technique has potential for a dual function - as a scrubbing device for particulate emission control as well as a control for water vapor emissions.

7.4 Wastewater Disposal:

Disposal of wastewater resulting from the scrubbing process does not appear to pose significant environmental problems for either the model system or for a potential full-scale installation at the University of Alaska.

7.5 General:

At this point we do not believe that scale-up of this technology for incorporation in operational power plant facilities is feasible. Therefore vital economic analyses pertinent to the system cannot be made at this time.

8. RECOMMENDATIONS

The limited success of this project and the previous work of Porteous and Wallis suggest there remains a potential for this technology to fulfill a useful function in control of combustion produced water vapor, but that further development and demonstration are needed. To aid in this process we present the following recommendations based on experience gained during the course of this project.

Continued research is necessary to further develop this technique for control of ice fog.

Future research should concentrate on the design of systems to minimize and ultimately eliminate the water entrainment problem.

Future experimental facilities should be self-contained to avoid the control problems associated with dependence on an operational facility. It would also be ideal if an experimental system was designed to burn oil as well as coal to compare the treatment of alternate fuels.

Concerning the waste water disposal, and assuming any further development of this system were to be undertaken at the University of Alaska power plant, it is recommended that discharge into the Chena after settling should be pursued as a possible option for the scrubbing wastewater. It would certainly be cheaper than discharge into the Tanana 5 miles below the University power plant. Before this option is actively pursued, however, laboratory tests must be conducted to assess the impact of the supernatant on aquatic life. If these tests reveal problem areas, then the other two options should be pursued. Since it appears that surface discharge after settling may be acceptable for an effluent resulting from the use of untreated well water, it does not appear worthwhile to consider treating the supply water.

No matter where the wastewater is ultimately discharged, intermediate scale settling tests should be conducted. In this preliminary study, settling resulted in an appreciable reduction in turbidity in 1-liter containers. The addition of lime did not aid this process. Future tests should be conducted in larger basins at least several feet in diameter. Since the settleable matter appeared to be very fine it could be resuspended by secondary currents in sedimentation basins. Removing the sludge from the basin may have to be done very carefully. These and other phenomena should be studied by performing additional experiments. Various coagulants should be tested. Ultimate uses for the sludge should be studied. Current uses for sludge from flue gas desulfurization processes include landfill material and as a base for synthetic aggregates (Crowe, 1976).

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APPENDIX A

```
10  REAL LE
20  PRINT, '     COUNTER FLOW STACK DEHUMIDIFIER'
30  PRINT, '
40  PRINT, 'STACK HEIGHT (FT)'
50  READ, SH
60  PRINT, 'INLET GAS TEMPERATURE (F)'
70  READ, TGI
80  PRINT, 'INLET GAS VELOCITY (FPS)'
90  READ, VG
100  PRINT, 'INLET HUMIDITY RATIO (LBW/LBG)'
110  READ, WI
120  PRINT, 'DROP DIAMETER (IN)'
130  READ, D
140  D = D/12.
150  PRINT, 'SPRAY VELOCITY (FPS)'
160  READ, VW
170  PRINT, 'INLET WATER TEMPERATURE (F)'
180  READ, TWI
190  PRINT, 'INITIAL FLOW RATIO (LBW/LBG)'
200  READ, FI
210  PRINT, 'FINAL FLOW RATIO (LBW/LBG)'
220  READ, FF
230  FF = FF+.01
240  PRINT, ''
250  FR = FI
260  70 TWO = TWI + 10
270  TINC = 2.0
280  GO TO 20
290  10 TWO = TWO + TINC
300  20 X = SH/50
310  TG1 = TGI
320  WG1 = WI
330  TW2 = TWO
340  ND = FR*6/(3.1416*D**3)/62.4
350  AV = ND*3.1416*D*D*39.715/(TGI+460)
360  ID = 0
370  NEND = 50
380  DO 80 J=1, NEND
390  CW = 1.0
400  TA = (TG1+TW2)/2.
410  VR = VW+VG*(TG1+460)/(TGI+460)
420  VK = .0001147+(6.28E-7)*TA
430  TD = .0001568+(9.4894E-7)*TA
440  PR = VK/TD
450  RE = VR*D/VK
460  TK = (3.7339E-6)+(6.3011E-9)*TA
470  HC = TK*(2.0+.6*PR**.333*SQRT (RE))/D
480  DEN = 39.715/(TG1+460)
490  IF(ID.EQ.1) GO TO 102
500  101 DC = (2.397E-4)*((TA+460)/460)**1.81
510  GO TO 103
520  102 DC = (3.86779E-9)*((TA+460)*5./9.)**1.9415
530  103 CONTINUE
540  SC = VK/DC
550  CP = .24+.45*WG1

*
*
```

```
560   HD = DC*(2.0+.6*SC**.333*SQRT(RE))/D
570   LE = HC/(HD*DEN*CP)
580   WS = .001276*EXP(.0353699*TW2)
590   HWG = 1061+.45*TG1
600   HG1 = (.24+.45*WG1)*TG1+1061*WG1
610   HGSW = (.240+.45*WS)*TW2+1061*WS
620   DWG = DEN*HD*AV*X*(WG1-WS)
630   HFW2 = CW*(TW2-32)
640  DHG = DWG*(LE*(HG1-HGSW)/(WG1-WS)+HWG-1061*LE)
650   DTW = -DWG/(FR*CW)*HFW2+DHG/(FR*CW)
660   TW1 = TW2 - DTW
670   WG2 = WG1 - DWG
680   HG2 = HG1 - DHG
690   TG2 = (HG2-1061*WG2)/(.24+.45*WG2)
700   TG1 = TG2
710   WG1 = WG2
720   TW2 = TW1
730   80 CONTINUE
740   IF(TWI-TW1.LT.0.0) GO TO 85
750   GO TO 90
760   85 TWO = TWO - TINC
770   TINC = TINC/2.
780   90 IF(ABS(TWI-TW1).GT..1) GO TO 10
790  PRINT, 'FLOW RATIO =', FR
800  PRINT, 'FINAL WATER TEMPERATURE (F)', TWO
810  PRINT, 'LEAVING GAS TEMPERATURE (F)', TG2
820  PRINT, 'FINAL HUMIDITY RATIO (LBW/LBA)', WG2
830   PRD = ((WI-WG2)/WI)*100.
840   PRINT, 'PERCENT WATER REMOVED', PRD
850   PRINT,'  '
860   FR = FR+.5
870   IF (FR.LT.FF) GO TO 70
880   STOP

*
```

The Emission Parameter Analyzer consists of a control module, a sampling unit, probe assembly, and a monorail support with Staclamp®.

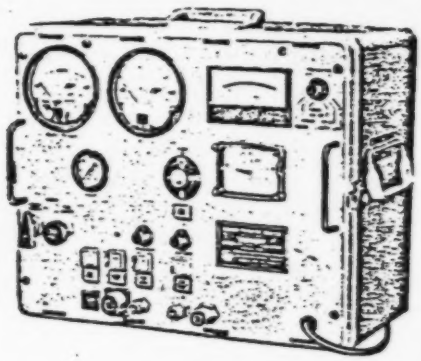

FIGURE 1

The control unit, Figure 1, contains all necessary operational controls, pressure and temperature measurement instrumentation, vacuum pump, dry gas meter, and timer mounted in a sturdy fiberglass case which also forms the shipping container.

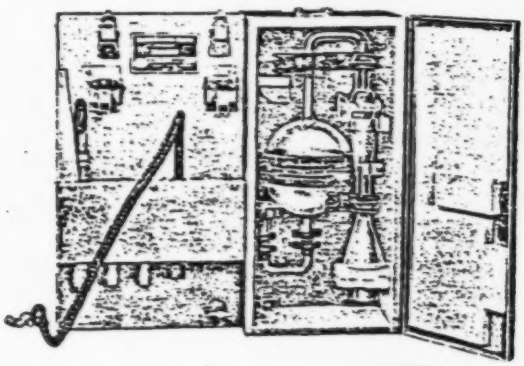

FIGURE 2

The sampling unit, Figure 2, consists of a stainless steel cabinet divided into two sections. The first section is a heated compartment containing provisions for a filter assembly and an optional cyclone; the second section is a compartment containing the impinger train or optional condenser. Openings in the cabinet and clamping devices are provided for attachment of the pitobe in either horizontal or vertical positions. Sampling train components are made of glass, joined by ball and socket joints and provided with clamping devices.

FIGURE 3

The standard pitobe, Figure 3*, has an effective length of 5 feet and consists of a sampling tube, a temperature probe, and a pitot tube. The sampling tube is a length of glass tubing running through the center of a stainless steel tube and terminating in a glass ball joint a short distance beyond the end of the stainless tube. The glass tubing is heated by a resistance element. Provision is made for use of a variety of sampling nozzles.

The pitot tube consists of a pair of stainless steel tubes attached to the assembly.

FIGURE 4

The monorail support is supplied in various lengths determined by the effective pitobe length. Guide rollers and clamps for the sample case and a Staclamp® used for attaching the monorail to a standard 3 inch test port are included with each unit. Figure 4 shows support structure.

*NOTE: Figure 3 is descriptive only; the tube shown is a special purpose 2 foot effective length assembly.

DATA SHEET

APPENDIX C

DATE	TIME	AMBIENT TEMP. (°F)	COOLING WATER FLOW (GPM)	INLET GAS PRESSURE (IN. H2O)	STACK PRESSURE (IN. H2O)	GAS VELOCITY (F.P.S.)	INLET WATER TEMP. (°F)	DRAIN WATER TEMP. (°F)	GAS INLET TEMP. (°F)	GAS OUTLET TEMP. (°F)	INLET HUMIDITY	OUTLET HUMIDITY	REMARKS
1/13/78	11:30	+14	0	-0.3	+0.04	no reading	--	--	-	-	-	-	Pitot tube orifice plugged (remove & clean); stack outlet gas temp. does not register
1/13/78	12:00	+14	30	0	0	no reading	73	93	398	-	-	-	
1/13/78	12:05	+14	40	0	0	no reading	--	90	-	-	-	-	
1/13/78	12:10	+14	20	0	0	no reading	--	103	-	-	-	-	
1/13/78	12:15	+14	15	0	0	no reading	--	109	-	-	-	-	
1/13/78	12:20	+14	25	0	0	no reading	--	98	-	-	-	-	
1/13/78	12:30	+14	41	0	0	no reading	--	--	376	-	-	-	Gas inlet damper 3/4 closed (only a very small plume is visible at the stack outlet)
1/18/78	10:30	+9	0	-0.24	-0.02	no reading	80	100	379	314	-	-	Stack outlet gas temp. thermocouples are replaced; Pitot tube cleaned out; inlet & stack gas pressure tape cleaned out
1/18/78		+10	5	-0.52	-0.02	no reading	76	102	380	201	-	-	All dampers fully open

DATA SHEET

DATE	TIME	AMBIENT TEMP. (°F)	COOLING WATER FLOW (GPM)	INLET GAS PRESSURE (IN. H2O)	STACK PRESSURE (IN. H2O)	GAS VELOCITY (F.P.S.)	INLET WATER TEMP. (°F)	DRAIN WATER TEMP. (°F)	GAS INLET TEMP. (°F)	GAS OUTLET TEMP. (°F)	INLET HUMIDITY	OUTLET HUMIDITY	REMARKS
1/18/78		+9	10	+0.06	+0.10	no reading	75	107	380	163	-	-	
1/18/78		+9	15	+0.10	+0.14	no reading	75	103	379	146	-	-	
1/18/78		+10	20	+0.14	+0.14	no reading	74	100	378	124	-	-	
1/18/78		+12	25	+0.10	+0.20	no reading	73	92	378	120	-	-	
1/18/78		+10	30	+0.08	+0.08	no reading	74	90	377	122	-	-	
1/18/78		+14	35	+0.32	+0.04	no reading	74	86	375	124	-	-	Again cleaned Pitot tube; also cleaned gas pressure taps
1/18/78		+12	40	+0.10	+0.05	8.9	73	86	376	117	-	-	
1/18/78		+12	40	-2.10	+1.50	no reading	74	77	329	83	-	-	Inlet gas damper 3/4 closed
1/18/78		+15	35	-0.10	+1.02	no reading	73	76	320	78	-	-	

DATA SHEET

DATE	TIME	AMBIENT TEMP. (°F)	COOLING WATER FLOW (GPM)	INLET GAS PRESSURE (IN. H2O)	STACK PRESSURE (IN. H2O)	GAS VELOCITY (F.P.S.)	INLET WATER TEMP. (°F)	DRAIN WATER TEMP. (°F)	GAS INLET TEMP. (°F)	GAS OUTLET TEMP. (°F)	INLET HUMIDITY	OUTLET HUMIDITY	REMARKS
1/18/78		+14	30	+0.08	+0.05	no reading	74	76	321	77	-	-	
1/18/78		+13	25	+0.13	+0.05	no reading	73	77	321	76	-	-	
1/18/78		+12	20	+0.05	+0.11	no reading	73	79	321	75	-	-	
1/18/78		+13	15	+0.13	+0.06	no reading	73	81	321	74	-	-	
1/18/78		+14	10	+0.11	+0.11	no reading	74	83	321	75	-	-	
1/18/78		+17	5	+0.24	+0.20	no reading	74	88	321	80	-	-	
1/19/78	10:30	+22	0	-0.32	+0.26	12.25	81	91	385	293	-	-	Hot flue gas was run through stack to dry out walls; cooling water nozzle was plumbed to correct alignment (dampers open)
1/19/78	10:45	+22	40	-0.94	+0.86	11.7	73	89	392	123	-	-	
1/19/78	11:00	+24	35	+0.08	+0.02	10.8	73	88	393	119	-	-	

DATA SHEET

DATE	TIME	AMBIENT TEMP. (°F)	COOLING WATER FLOW (GPM)	INLET GAS PRESSURE (IN. H2O)	STACK PRESSURE (IN. H2O)	GAS VELOCITY (F.P.S.)	INLET WATER TEMP. (°F)	DRAIN WATER TEMP. (°F)	GAS INLET TEMP. (°F)	GAS OUTLET TEMP. (°F)	INLET HUMIDITY	OUTLET HUMIDITY	REMARKS
1/19/78	11:10	+29	30	+0.70	+1.00	9.8	74	93	396	129	-	-	Pitot tube may be plugged
1/19/78	11:20	+21	25	+0.16	+1.06	11.75	73	95	399	130	-	-	
1/19/78	11:30	+17	20	+0.22	+0.15	12.25	73	103	400	125	-	-	
1/19/78	11:40	+22	10	+0.36	+0.18	12.4	74	112	398	170	-	-	During this series of tests one could stand outside below the stack and feel the mist which is evidently carried over the stack outlet (after the tests all cars in the parking lot below the stack had a glaze of ice covering the windshields although nowhere was this icing observed)
1/20/78	~10:00	+27	0	+0.26	+0.09	13.2	82	134	404	256	-	-	All dampers fully open; Pitot tube cleaned before start of testing
1/20/78	10:30	+26	46	+0.14	+0.24	13.2	73	88	404	109	-	-	
1/20/78	10:40	+26	44	+0.10	+0.04	12.75	73	89	403	113	-	-	

DATA SHEET

DATE	TIME	AMBIENT TEMP. (°F)	COOLING WATER FLOW (GPM)	INLET GAS PRESSURE (IN. H20)	STACK PRESSURE (IN. H20)	GAS VELOCITY (F.P.S.)	INLET WATER TEMP. (°F)	DRAIN WATER TEMP. (°F)	GAS INLET TEMP. (°F)	GAS OUTLET TEMP. (°F)	INLET HUMIDITY	OUTLET HUMIDITY	REMARKS
1/20/78	10:50	+28	42	+0.08	+0.10	12.6	73	90	406	116	-	-	
1/20/78	11:00	+26	40	0.00	+0.08	12.6	73	90	401	119	-	-	
1/20/78	11:08	+24	38	+0.10	+0.05	13.2	73	91	403	122	-	-	
1/20/78	11:14	+24	36	+0.10	+0.10	13.2	73	91	404	91	-	-	
1/20/78	11:21	+24	34	+0.10	+0.15	12.75	73	92	403	126	-	-	
1/20/78	11:27	+24	32	+0.04	+0.10	13.2	73	92	404	127	-	-	
1/20/78	11:33	+25	30	+0.12	+0.22	13.2	73	93	405	130	-	-	
1/20/78	11:39	+24	28	+0.17	+0.14	13.2	73	94	404	130	-	-	
1/20/78	11:45	+23	26	+0.12	+0.06	13.2	73	96	405	129	-	-	

DATA SHEET

DATE	TIME	AMBIENT TEMP. (°F)	COOLING WATER FLOW (GPM)	INLET GAS PRESSURE (IN. H2O)	STACK PRESSURE (IN. H2O)	GAS VELOCITY (F.P.S.)	INLET WATER TEMP. (°F)	DRAIN WATER TEMP. (°F)	GAS INLET TEMP. (°F)	GAS OUTLET TEMP. (°F)	INLET HUMIDITY	OUTLET HUMIDITY	REMARKS
1/20/78	11:52	+24	24	+0.18	+0.12	12.4	73	98	398	122	-	-	
1/20/78	11:58	+24	23	+0.10	+0.03	13.2	73	99	399	119	-	-	
1/20/78	12:05	+24	22	+0.12	+0.12	13.2	73	100	401	117	-	-	
1/20/78	12:12	+26	21	+0.15	+0.16	13.2	73	102	405	122	-	-	
1/20/78	12:15	+23	20	+0.24	+0.14	13.2	73	104	406	125	-	-	During the series of tests on 1/20/78 we periodically went outside to see if carryover water could be noticed. Each time when looking up toward the top of the stack a light mist of rain could be felt on the face. Carryover was felt at all flow rates.
1/20/78	12:20	+23	15	+0.12	+0.20	13.2	73	107	406	145	-	-	
2/8/78	14:00	-15	38	+0.20	+0.25	10.3	57	73	403	110	-	-	Light snow falling; inlet damper fully open; water line has been replumbed to use raw water at cooler temperature.
2/8/78	14:05	-15	38	+0.20	+0.23	10.3	57	74	403	109	-	-	
2/8/78	14:10	-15	37½	+0.20	+0.23	10.3	57	73	401	109	-	-	

DATA SHEET

DATE	TIME	AMBIENT TEMP. (°F)	COOLING WATER FLOW (GPM)	INLET GAS PRESSURE (IN. H2O)	STACK PRESSURE (IN. H2O)	GAS VELOCITY (F.P.S.)	INLET WATER TEMP. (°F)	DRAIN WATER TEMP. (°F)	GAS INLET TEMP. (°F)	GAS OUTLET TEMP. (°F)	INLET HUMIDITY	OUTLET HUMIDITY	REMARKS
2/8/78	16:08	-15	37	-	-	6.5	55	67	367	93	-	-	This series of tests was run with inlet damper fully closed
2/8/78	16:13	-15	38	+0.22	+0.22	6.5	56	68	367	92	-	-	The spray pattern does not seem too reach to the full outside diameter of stack; new nozzle should be considered
2/21/78	Arrived to find that the power plant personnel had shut down boiler to clean blades of main I.D. fan. There appears to be a build-up of sooty material collecting on blades. This has apparently never happened before and may be caused by our experimental system. The problem was detected by an imbalance in the blades which resulted in vibration. We also installed a new nozzle.												
2/21/78	13:42	+46	0	+0.14	+0.12	7.3	62	118	350	201	-	-	Testing was done with main damper fully closed
2/21/78	13:50	+49	10	+0.38	+0.10	8.0	56	87	322	135	-	-	
2/21/78	14:03	+46	15	+0.14	+0.14	6.5	57	85	350	115	-	-	
2/21/78	14:19	+48	20	+0.32	+0.14	6.5	57	85	355	108	-	-	Inspected spray pattern...appears much better than old nozzle; spray seems to be evenly distributed over entire stack diameter
2/21/78	14:41	+48	22	+0.20	+0.20	7.3	54	74	350	89	-	-	
2/21/78	14:45	+47	24	+0.14	+0.14	7.3	54	72	346	87	-	-	

DATA SHEET

DATE	TIME	AMBIENT TEMP. (°F)	COOLING WATER FLOW (GPM)	INLET GAS PRESSURE (IN. H20)	STACK PRESSURE (IN. H20)	GAS VELOCITY (F.P.S.)	INLET WATER TEMP. (°F)	DRAIN WATER TEMP. (°F)	GAS INLET TEMP. (°F)	GAS OUTLET TEMP. (°F)	INLET HUMIDITY	OUTLET HUMIDITY	REMARKS
2/21/78	14:51	+48	26	+0.20	+0.20	8.0	54	73	362	89	-	-	
2/21/78	14:56	+48	28	+0.04	+0.10	8.0	54	73	359	87	-	-	
2/21/78	15:03	+49	30	+0.22	+0.18	8.0	53	71	355	81	-	-	
2/21/78	15:10	+47	34½	+0.10	+0.14	8.0	53	69	353	76	-	-	
2/24/78	14:00	+42	0	-	-	6.5	66	146	400	328	-	-	During these test series water samples were taken from drain; gas samples also taken; main damper closed
2/24/78	test begin 14:34	+46	10	-	-	6.0	65	107	397	166	-	-	Water sample taken D-135M
2/24/78	test end 14:50	+45	13	-	-	6.0	68	103	396	143	-	-	
2/24/78	test begin 14:55	+44	17	-	-	5.5	70	101	396	132	-	-	Water sample taken -D85
2/24/78	test end	+46	17	-	-	5.5	70	99	393	128	-	-	

DATA SHEET

DATE	TIME	AMBIENT TEMP. (°F)	COOLING WATER FLOW (GPM)	INLET GAS PRESSURE (IN. H2O)	STACK PRESSURE (IN. H2O)	GAS VELOCITY (F.P.S.)	INLET WATER TEMP. (°F)	DRAIN WATER TEMP. (°F)	GAS INLET TEMP. (°F)	GAS OUTLET TEMP. (°F)	INLET HUMIDITY	OUTLET HUMIDITY	REMARKS
2/24/78	test begin 15:20	+43	40	-	-	5.5	67	85	394	84	-	-	Water sample taken (Chena River); Gas sample taken
2/24/78	test end 15:40	+45	35	-	-	5.5	56	77	395	79	-	-	
3/2/78	test begin 11:15	+35	0	-	+0.20	9.75	62	101	414	346	-	-	No water sample; gas sample no good
3/2/78	test end 11:30	-	-	-	-	12.7	-	-	-	-	-	-	
3/2/78	test begin 11:40	+38	10	-	+0.24	8.2	57	106	419	149	-	-	Water sample taken and discarded; gas sample no good
3/2/78	test end 12:00	+42	10	-	-	7.5	57	108	424	143	-	-	
3/2/78	test begin 12:05	+43	15	-	-	9.75	58	99	423	125	-	-	Water sample taken and discarded; gas sampling equipment broke down so test was no good
3/2/78	test end 12:17	+41	15	-	-	9.3	58	101	436	124	-	-	
3/2/78	12:20 to 12:25	+40	20	-	-	9.1	57	93	444	109	-	-	Water sample taken and discarded; no gas sample

DATA SHEET

DATE	TIME	AMBIENT TEMP. (°F)	COOLING WATER FLOW (GPM)	INLET GAS PRESSURE (IN. H2O)	STACK PRESSURE (IN. H2O)	GAS VELOCITY (F.P.S.)	INLET WATER TEMP. (°F)	DRAIN WATER TEMP. (°F)	GAS INLET TEMP. (°F)	GAS OUTLET TEMP. (°F)	INLET HUMIDITY	OUTLET HUMIDITY	REMARKS
3/2/78	test begin 12:45	+39	25	--	-	9.75	55	85	436	94	-	-	Gas sampler has been repaired; gas and water samples taken
3/2/78	test end 13:05	+38	25	-	-	5.2	56	85	431	91	-	-	Pitot tube plugged during test
3/2/78	test begin 13:10	+39	30	-	-	5.8	56	83	432	85	-	-	Water sample taken, gas sample taken
3/2/78	test end 13:30	+40	30	-	-	13.0	55	81	430	82	-	-	Pitot tube cleared itself during test
3/2/78	test begin 13:40	+42	31	-	-	7.3	55	80	434	81	-	-	Gas sample taken, water sample taken
3/2/78	test end 13:55	+42	31	-	-	7.3	55	80	434	81	-	-	Flow rate unstable, varies 35-31
3/2/78	test begin 14:00	+43	20	-	-	8.2	57	90	434	96	-	-	Gas sample taken, water sample taken
3/2/78	test end 14:20	+40	20	-	-	9.5	59	92	434	94	-	-	

DATA SHEET

DATE	TIME	AMBIENT TEMP. (°F)	COOLING WATER FLOW (GPM)	INLET GAS PRESSURE (IN. H2O)	STACK PRESSURE (IN. H2O)	GAS VELOCITY (F.P.S.)	INLET WATER TEMP. (°F)	DRAIN WATER TEMP. (°F)	GAS INLET TEMP. (°F)	GAS OUTLET TEMP. (°F)	INLET HUMIDITY	OUTLET HUMIDITY	REMARKS
3/2/78	test begin 14:25	+40	15	-	-	8.5	62	102	434	112	-	-	Water sample taken, gas sample taken
3/2/78	test end 14:40	+42	15	-	-	9.5	58	101	433	118	-	-	Gas sample taken, water sample taken
3/22/78	test begin 14:45	+42	10	-	-	10.75	59	108	432	136	-	-	Gas sample taken; water sample taken
3/22/78	test end 15:00	+38	10	-	-	11.5	58	108	430	143	-	-	
3/22/78	test begin 15:10	+36	0	-	-	11.0	60	117	428	259	-	-	Gas sample taken
3/22/78	test end 15:25	+36	0	-	-	11.0	66	93	424	312	-	-	
3/22/78	test begin 15:50	+35	0	-	-		65	92	318	185	-	-	Both inlet and main damper closed; gas sample taken; velocity manometer reads -.04
3/22/78	test end 16:00	+35	0	-	-		65	96	312	171	-	-	

DATA SHEET

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3/22/78	test begin 16:05	+34	10	-	-		60	70	313	57	-	-	Gas sample taken; water sample taken; velocity manometer reads -0.04
3/22/78	test end 16:15	+34	10	-	-		60	70	313	57	-	-	
3/22/78	16:30	+35	15	-	-		60	65	316	54	-	-	Water sample taken; gas sampler breaks down again! Velocity manometer reads -0.05